The little bang at RHIC

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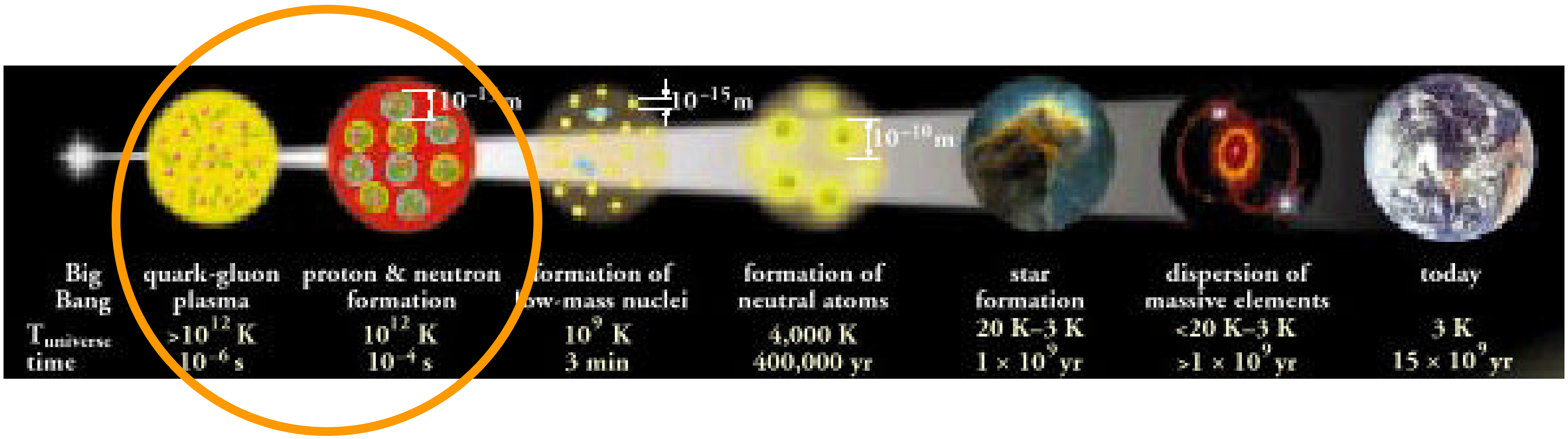
Outline

- What are we doing and why?
- What is RHIC?
- Where is RHIC?
- Brief description of PHENIX detector
- What do the collisions look like? Geometry?
- Measuring temperature
- Measuring density
- How close have we come to the early universe?
- Are there any signals?
- The future

Phase Transitions

- The phase transition from quarks and gluons to hadrons (protons, neutrons, and other strongly interacting particles) took place ~ 10 µsec after the Big Bang.

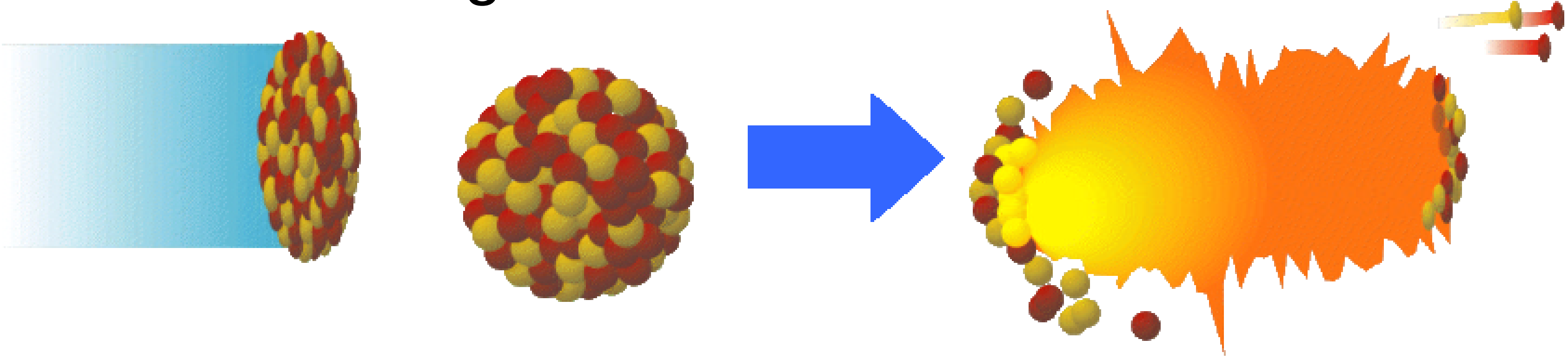


We hope to recreate a small piece of matter above 10^{12} °K, consisting of a plasma of quarks and gluons. We reach this state by colliding Au nuclei.

Boiling Nuclei

- Fundamental Method:

  Collide heavy nuclei at the highest possible energies:



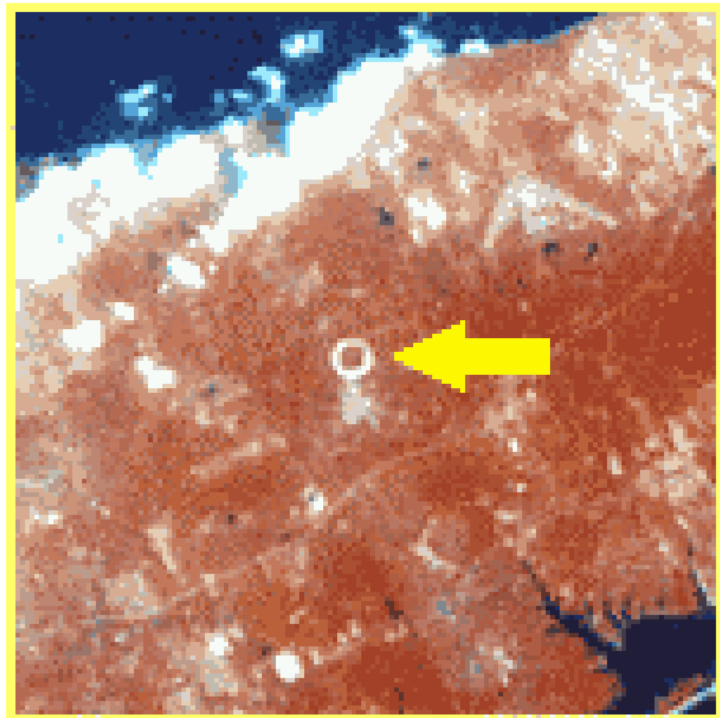
- **Fundamental Goals:**
  - **Create (new) dense forms of matter**
  - **Re-create the *quark-gluon phase transition***

The Relativistic Heavy Ion Collider at BNL

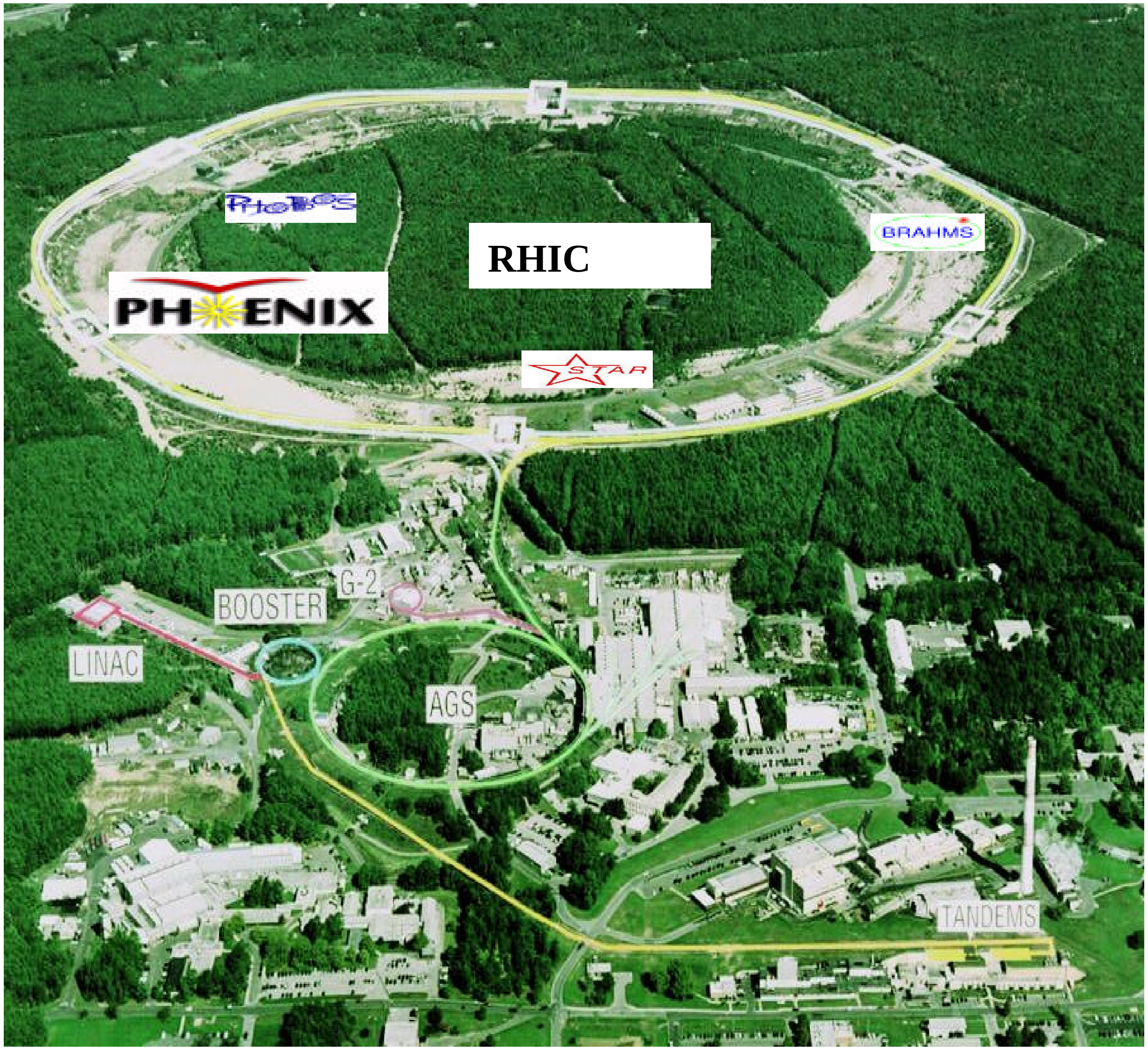
- Two independent rings 3.8 km in circumference
  - 106 ns crossing time
  - 6 “intersection regions” for experiments
- Maximum Energy for Au+Au:
  - 200 GeV per nucleon-nucleon collision
  - v/c ~ 0.99999
- Design Luminosity (measure of intensity)
  - Au-Au $2x10^{26}$ $cm^{-2}s^{-1}$
  - Translation: Multiply by the Au+Au interaction cross section (~$6.8x10^{-24}$ cm^{-2}) to get event rate
  - Event rate ~1360/sec
- Capable of colliding any nuclear species on any other nuclear species

You can see RHIC from space

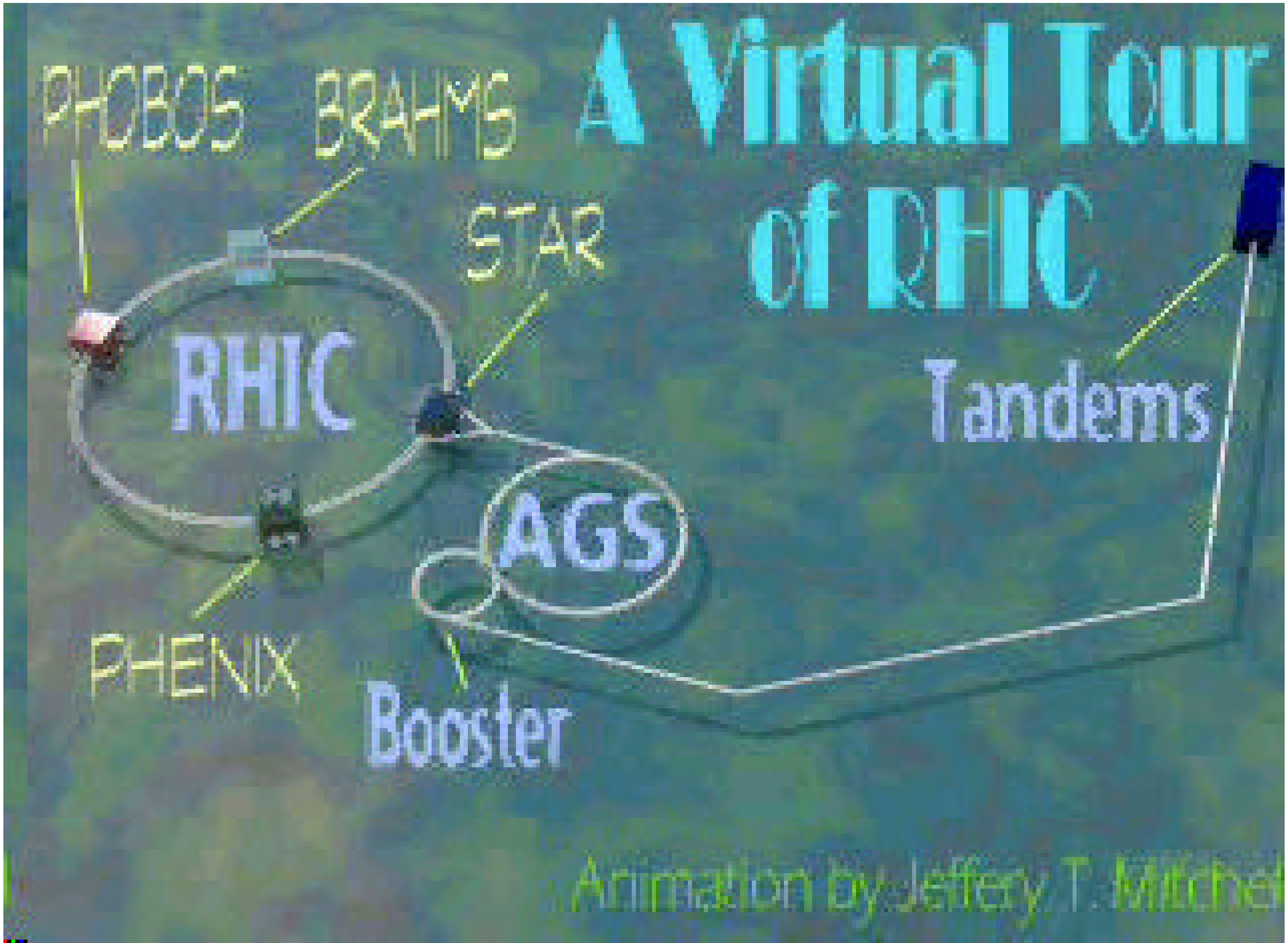
Picture taken in 1982 when the ring was under construction



The accelerator complex



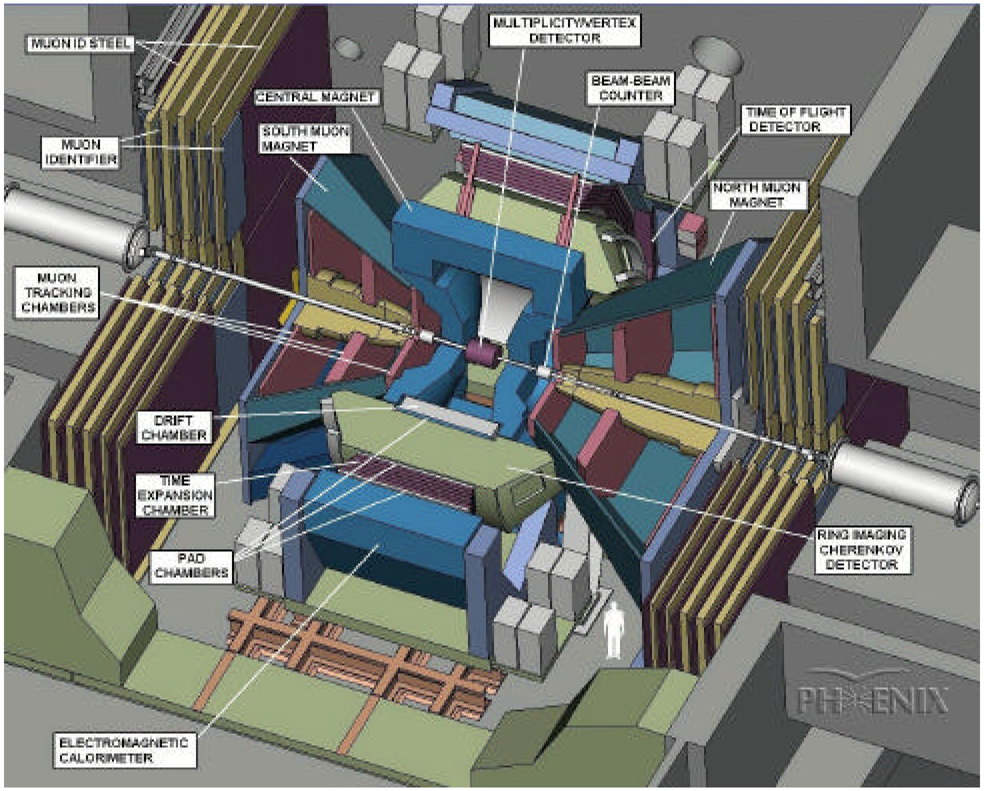
A virtual tour of RHIC



PHENIX detector

Tale of the Tape:

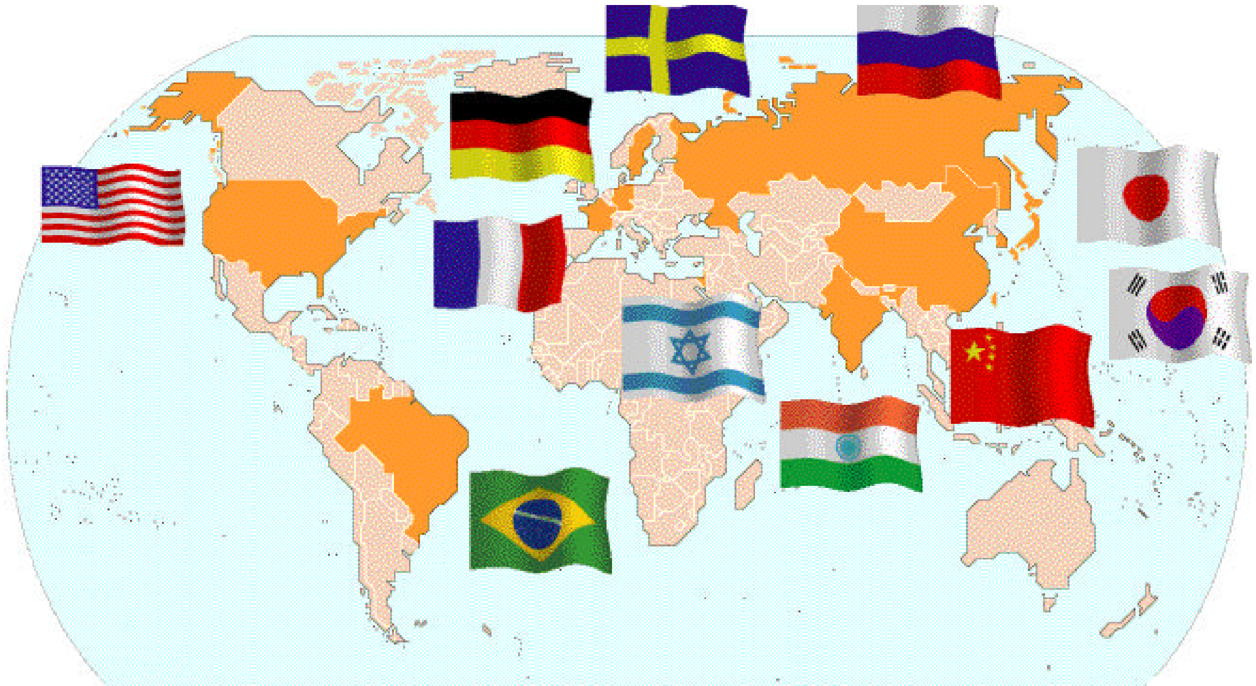
- ➢Began Operation June 2000
- ➢12 Detector subsystems
- ➢4 Spectrometer arms
- ➢Total weight = 3000T
- ➢315,000 readout channels
- ➢ >125 Varieties of custom printed circuit boards
- ➢13 ASICs designed specifically for PHENIX



The PHENIX Experiment is designed to probe fundamental features of the strong nuclear force including:

- •The detection and characterization of the Quark-Gluon Plasma
- •The spin structure of the nucleons

PHENIX



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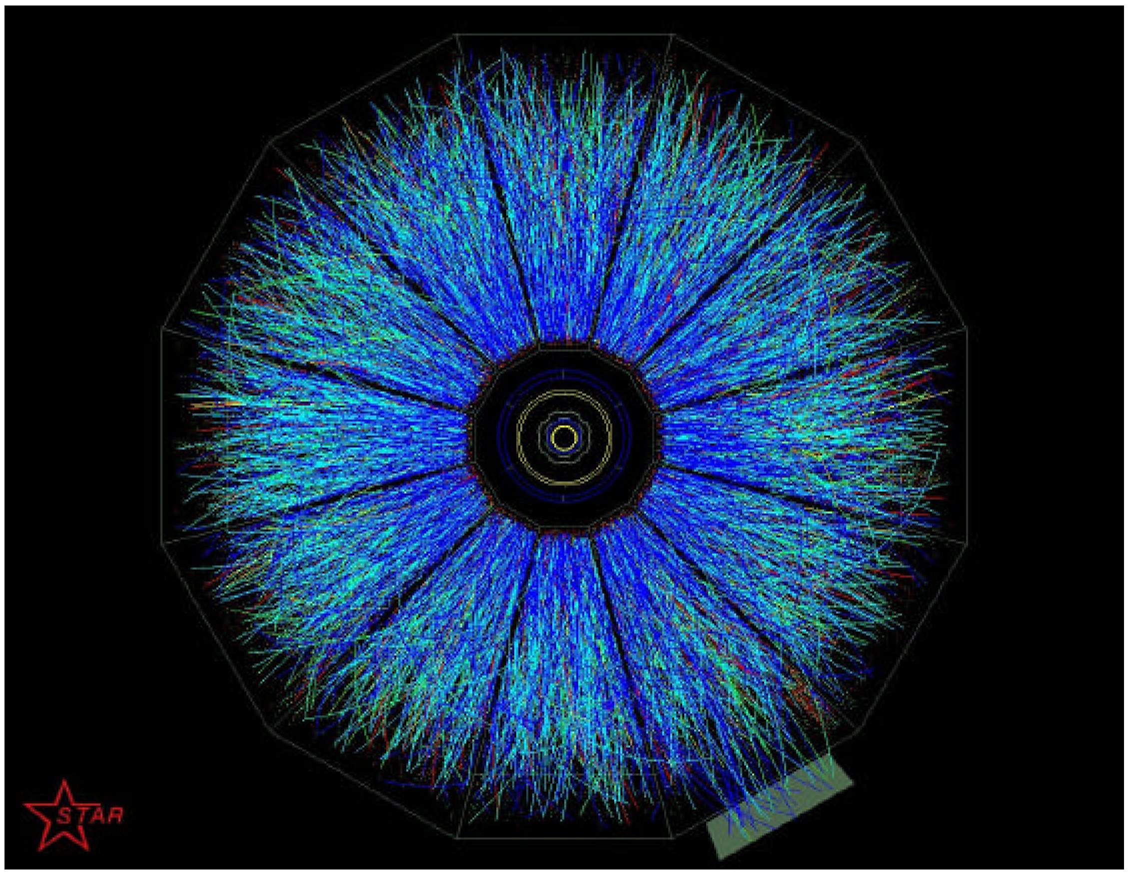
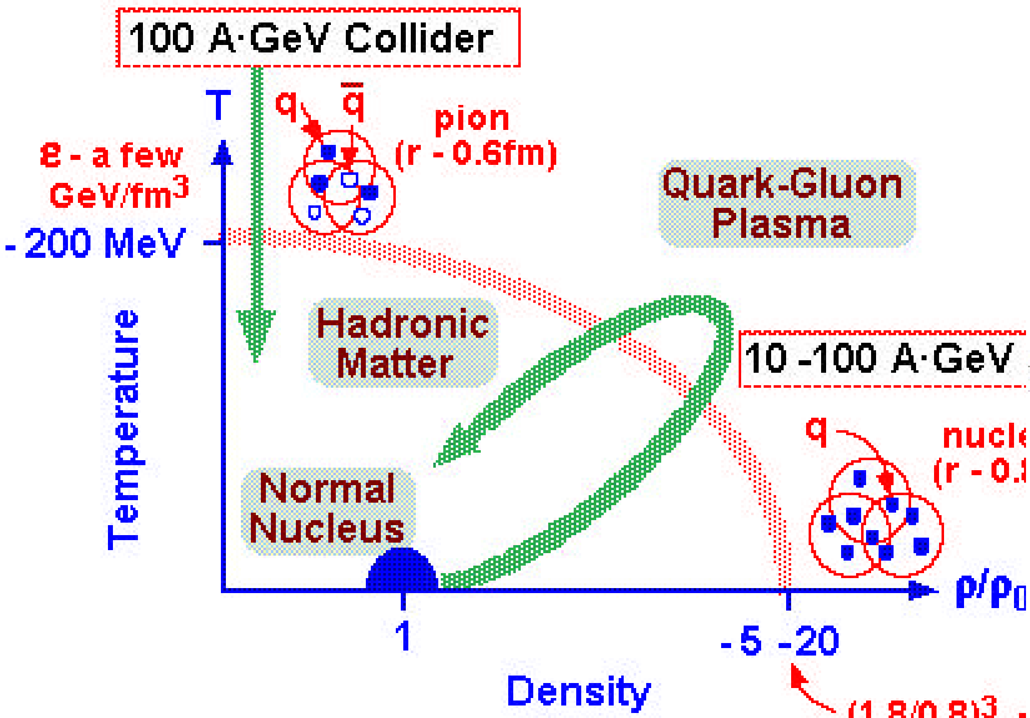
Vanderbilt University, Nashville, TN 37235, USA

A real Au+Au event

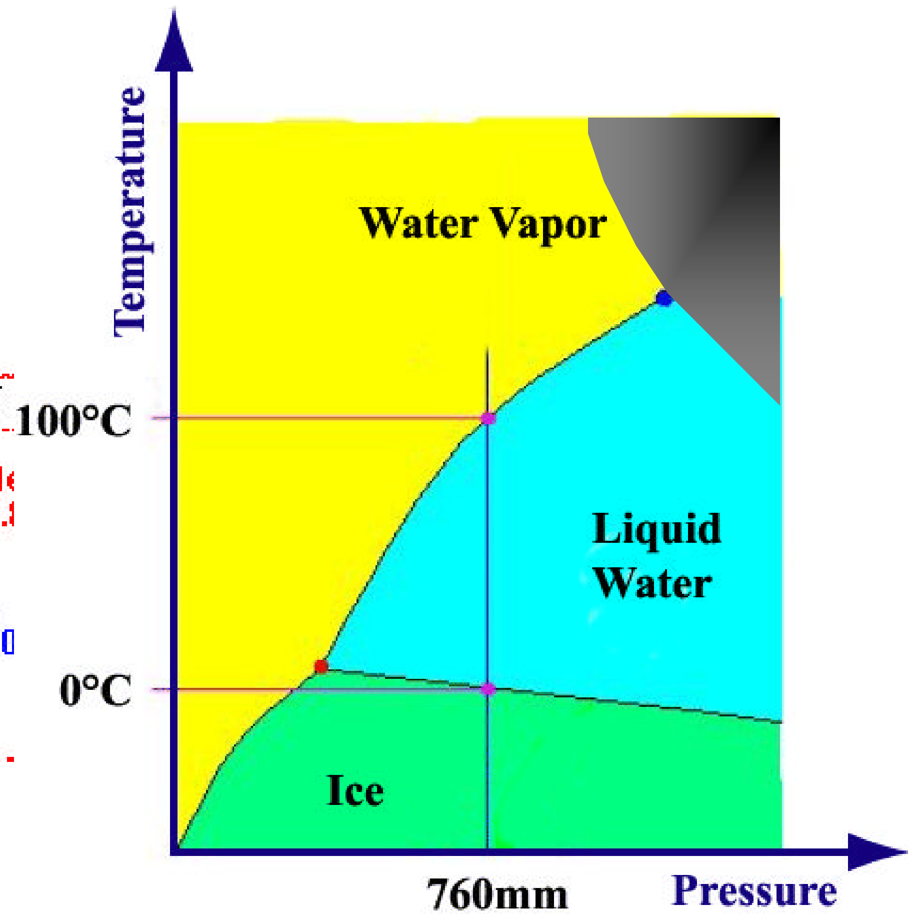
Looking down the beam line, a reconstructed event from the STAR collaboration:



Phase Diagrams



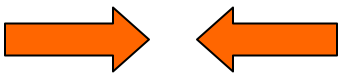
Nuclear Matter



Water

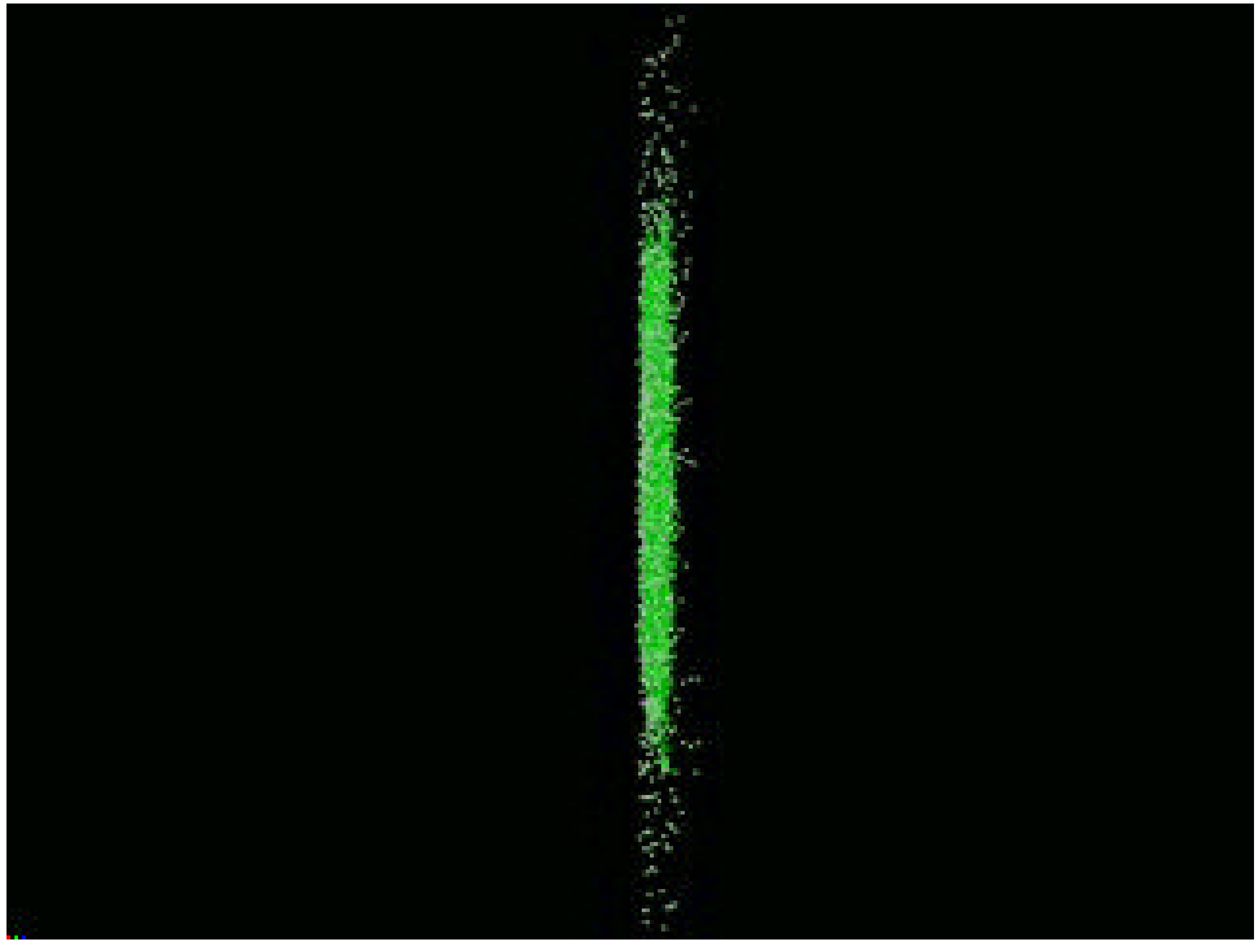
Model calculation

Starts just prior to the collision



Beam directions

Beam nuclei Lorentz contracted in lab frame

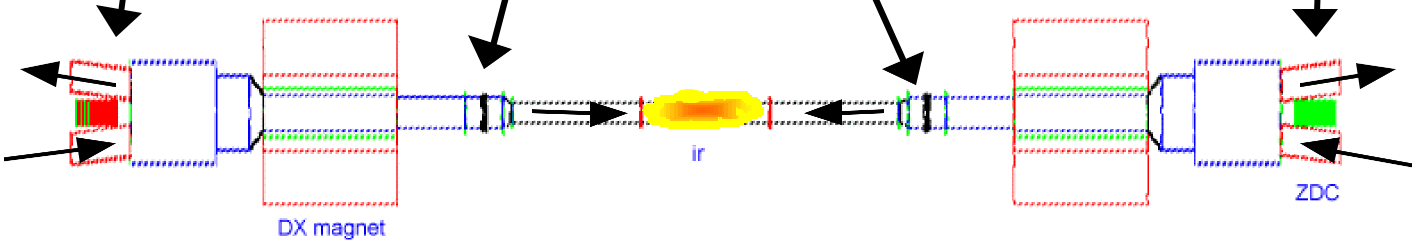


Animation my Jeff Mitchell (BNL)
VNI collision model by K. Kinder-Geiger, R. Longacre

Measuring the collision geometry

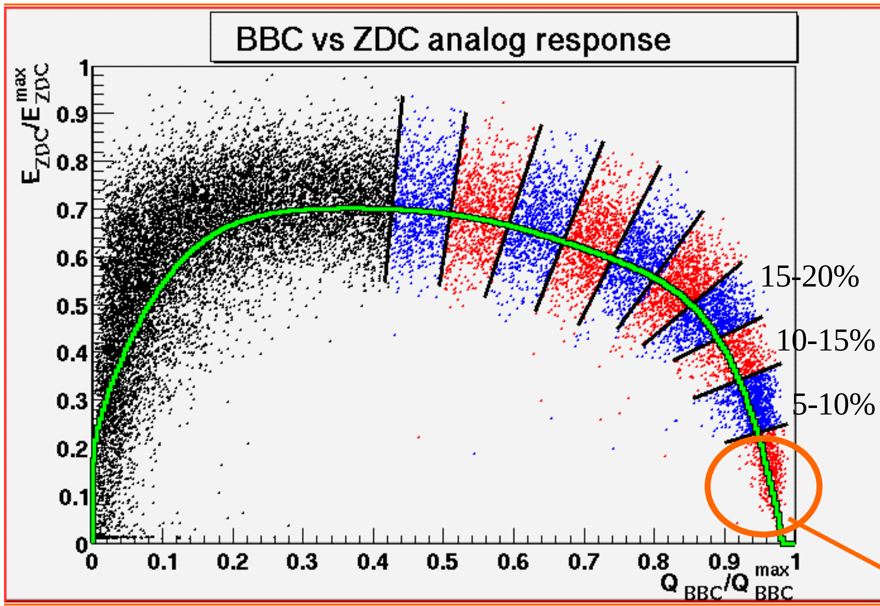
Zero Degree Calorimeters (ZDC's) are about 18 m from the interaction region, one on each side. They measure "spectator" neutrons.

The beam beam counters (BBC) are at +-3.5 m. They measure charged "participants".

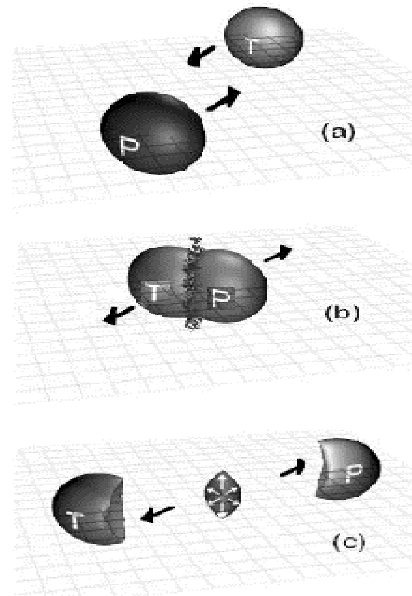


Events are characterized via a 2D plot of these two detectors.

Determining N(participants)



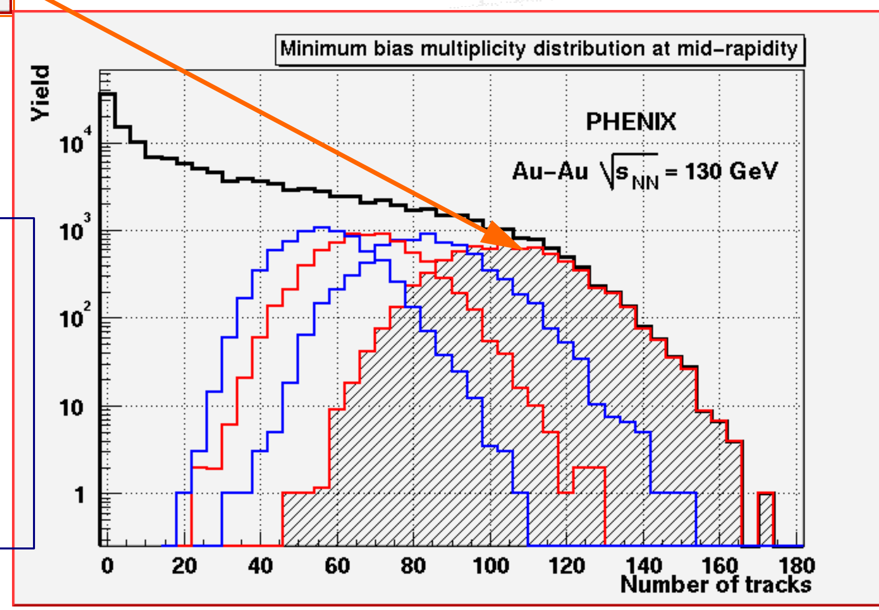
ZDC/ZDC max



BBC/BBCmax

2R ← impact parameter ← 0

BBC vs ZDC centrality is correlated with the number of charged particles in the central detector arms:



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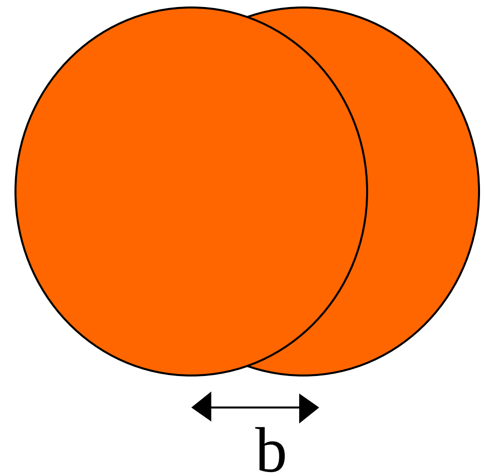
Geometry

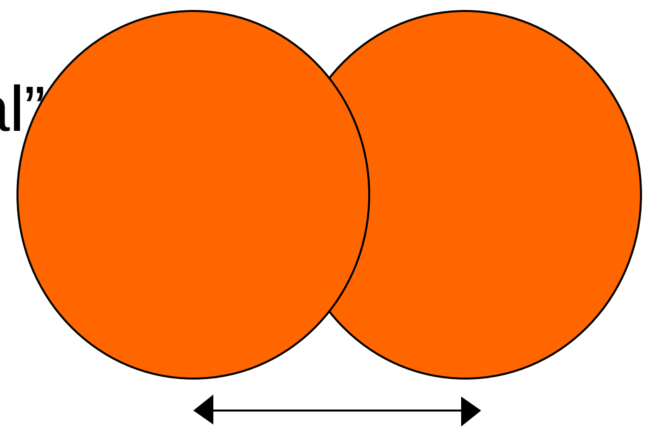
Two nuclei, one going into the page, the other out:

There is an almond-shaped overlap region, nucleons in this volume are called “participants”, the others continue on at ~ their original momentum and are called “spectators”.

“central” collision ($b \rightarrow 0$)



“peripheral” collision ($b \rightarrow 2R$)



b = impact parameter

Elliptic flow

The matter formed in the collision is initially very hot (kT ~ 200 MeV or ~2.4×10^{12} °K)

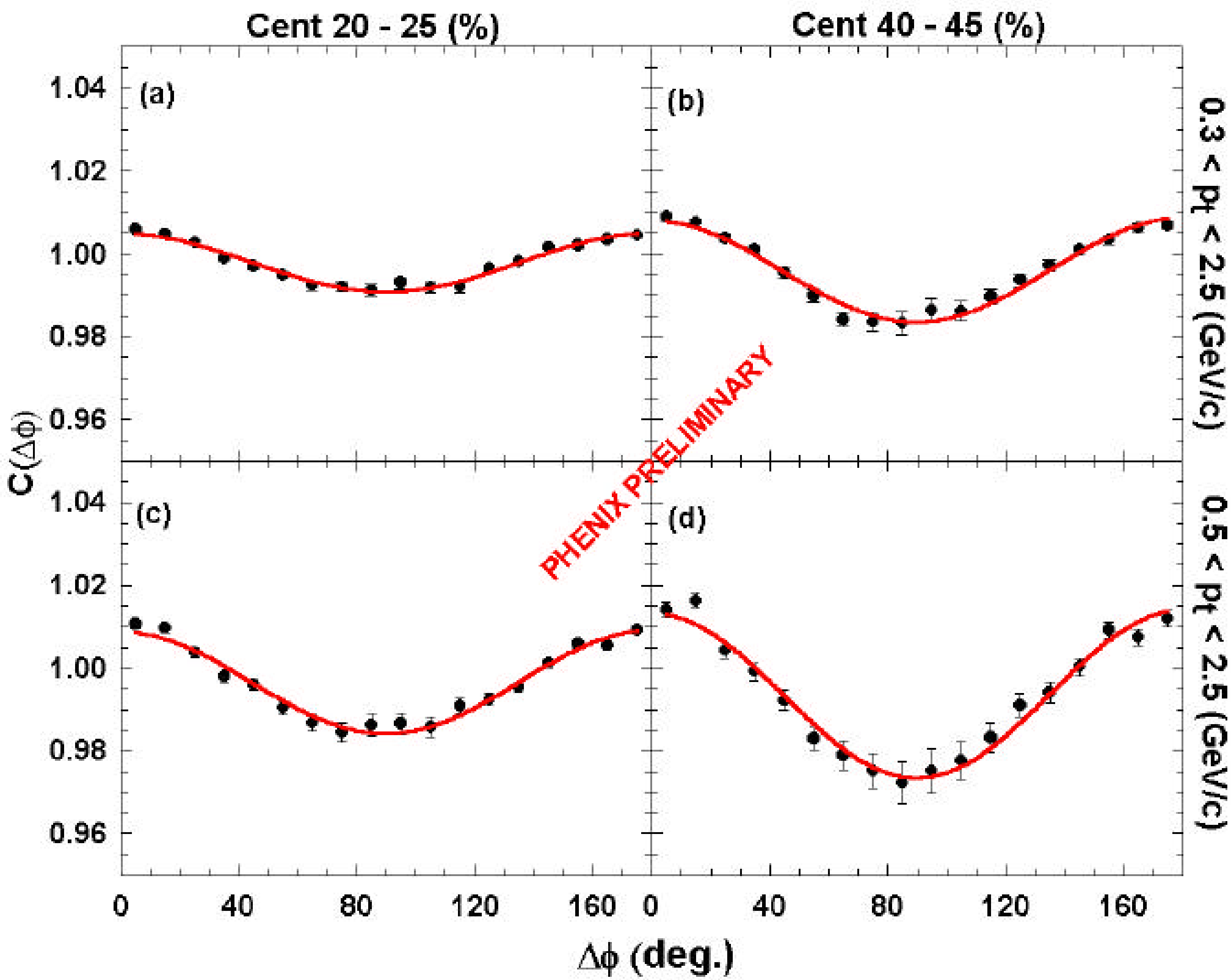
There is a lot of pressure pushing the material out from the center. The matter tends to “flow” outward. The details can be used to estimate the initial pressure.

A remnant of the initial almond-shaped overlap region (the “participants”) can be seen in the elliptic flow

Determine via a correlation function method
$C(\Delta\phi) = R(\Delta\phi)/B(\Delta\phi)$

$R(\Delta\phi)$ = number of pairs in real events
$B(\Delta\phi)$ = number of pairs in “mixed” events

Correlation Functions



V_2 shows clear centrality and p_T dependence

How do we determine temperature?

Boltzmann distribution: $dN/dp^3 \sim \exp(-E/T)$

E = energy(mass + kinetic) = γmc^2, $\gamma = (1-b^2)^{-½}$

T = temperature (really kT)

Relativistically, dN/dp^3 depends on the frame of reference, therefore, the Lorentz-invariant form is usually used: $dN/(dp^3/\gamma) \sim E\, dN/dp^3$

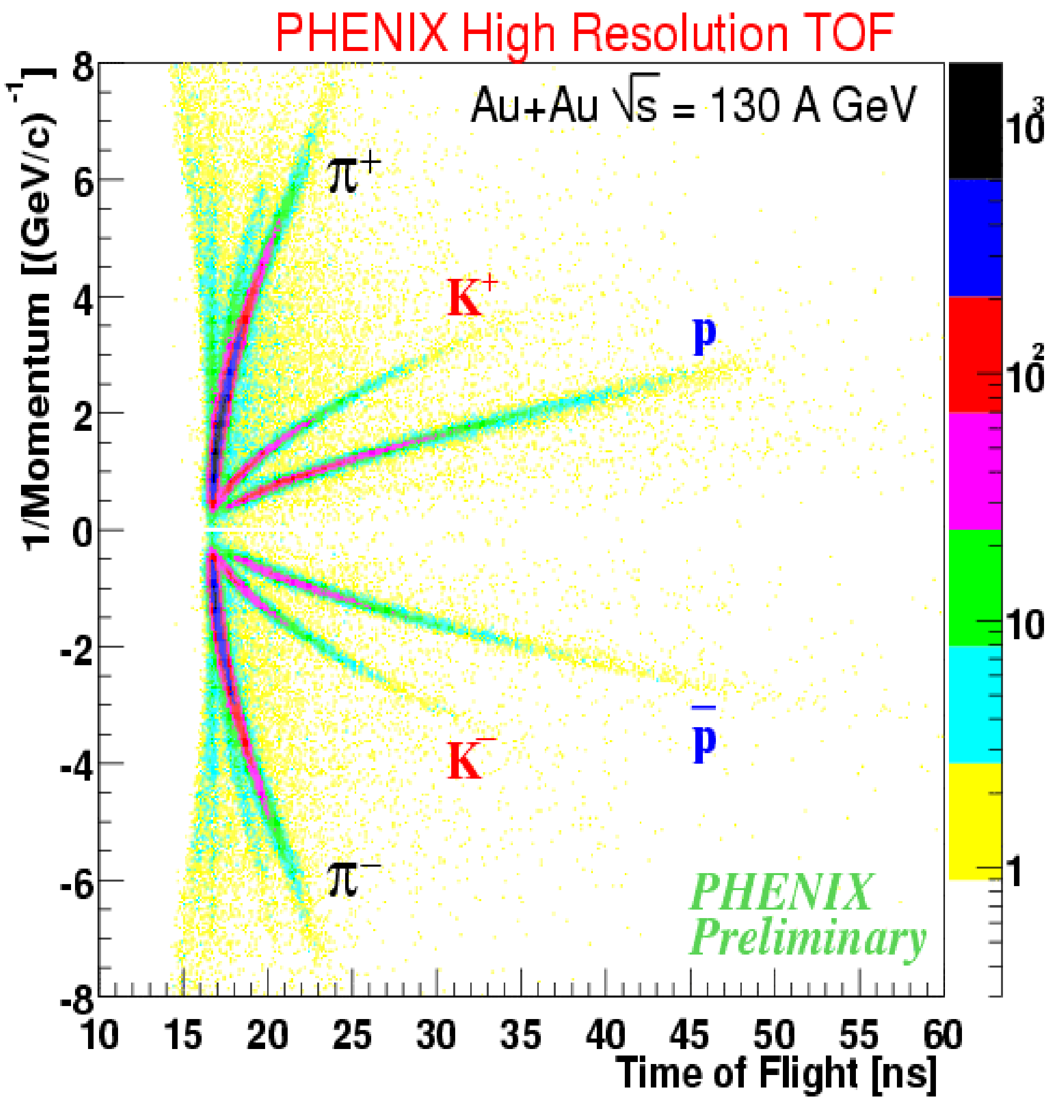
dN/dp^3 can be expressed as p^2dpd(cosè)dö

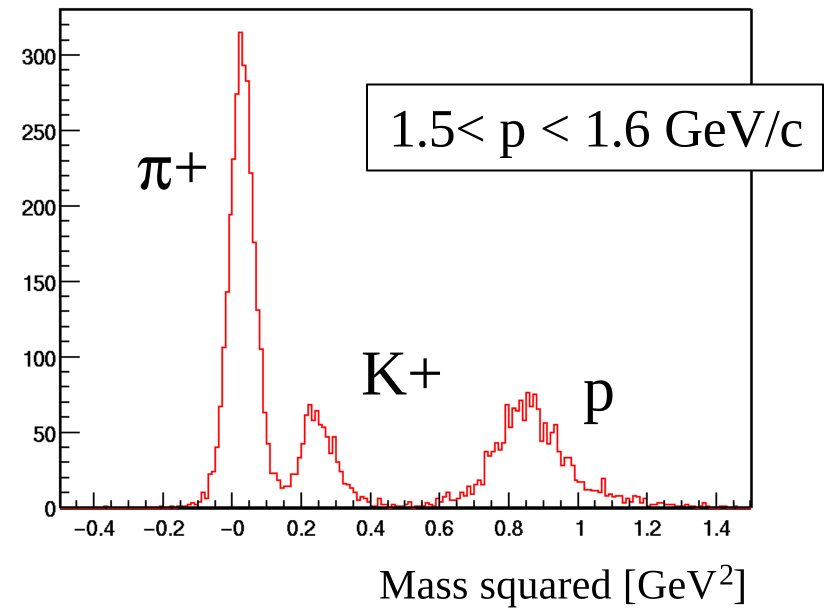
At è = 90^o (transverse to the beam), then $p = p_T$, pick d(cosè) and dö independent of p_T, then:

$dN/dp^3 \sim (1/p^2)\, dN/dp_T$

We measure the number of particles in a bin of p_T divided by $p_T{}^2$ and miscellaneous factors which are not important for this discussion.

Particle identification via TOF





π/K separation < 1.6 GeV/c
Proton separation < 3.5 GeV/c

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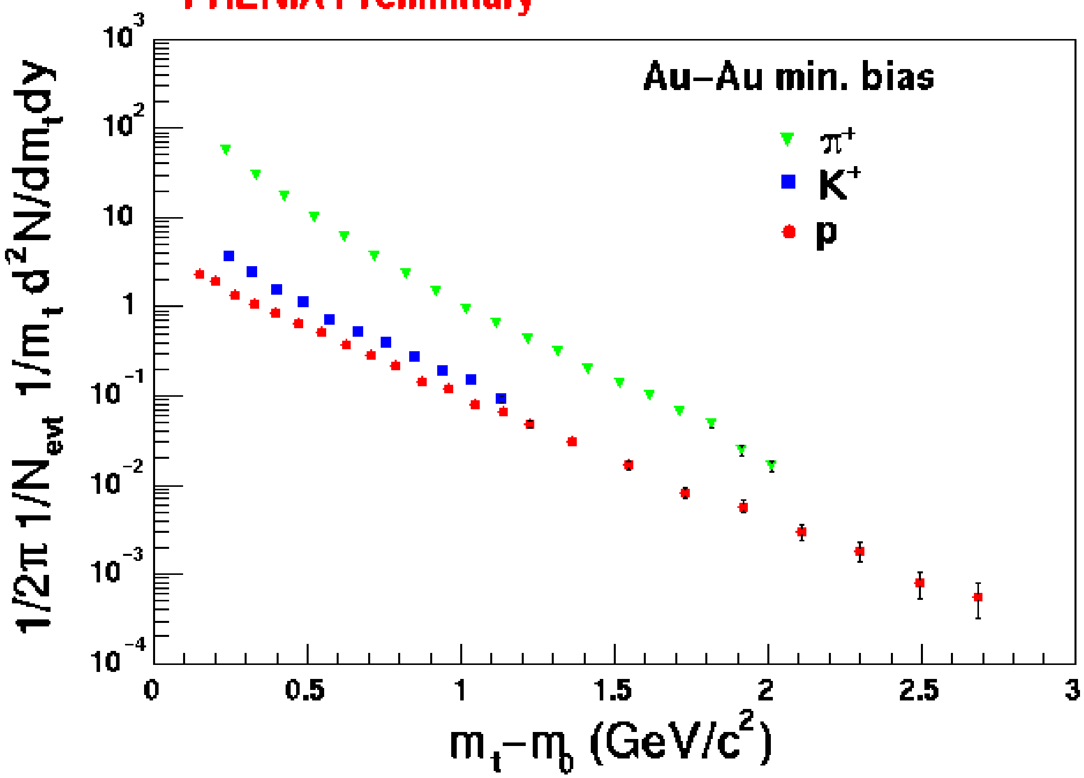
M_T Spectra

$E\, dN/dp^3$ =



- $m_T^2 = p_T^2 + m^2$ (=E at 90°)
- **Slopes of transverse mass spectra increase with particle mass**
- **Not all particles have the same slope, so it is hard to call this slope a temperature.**

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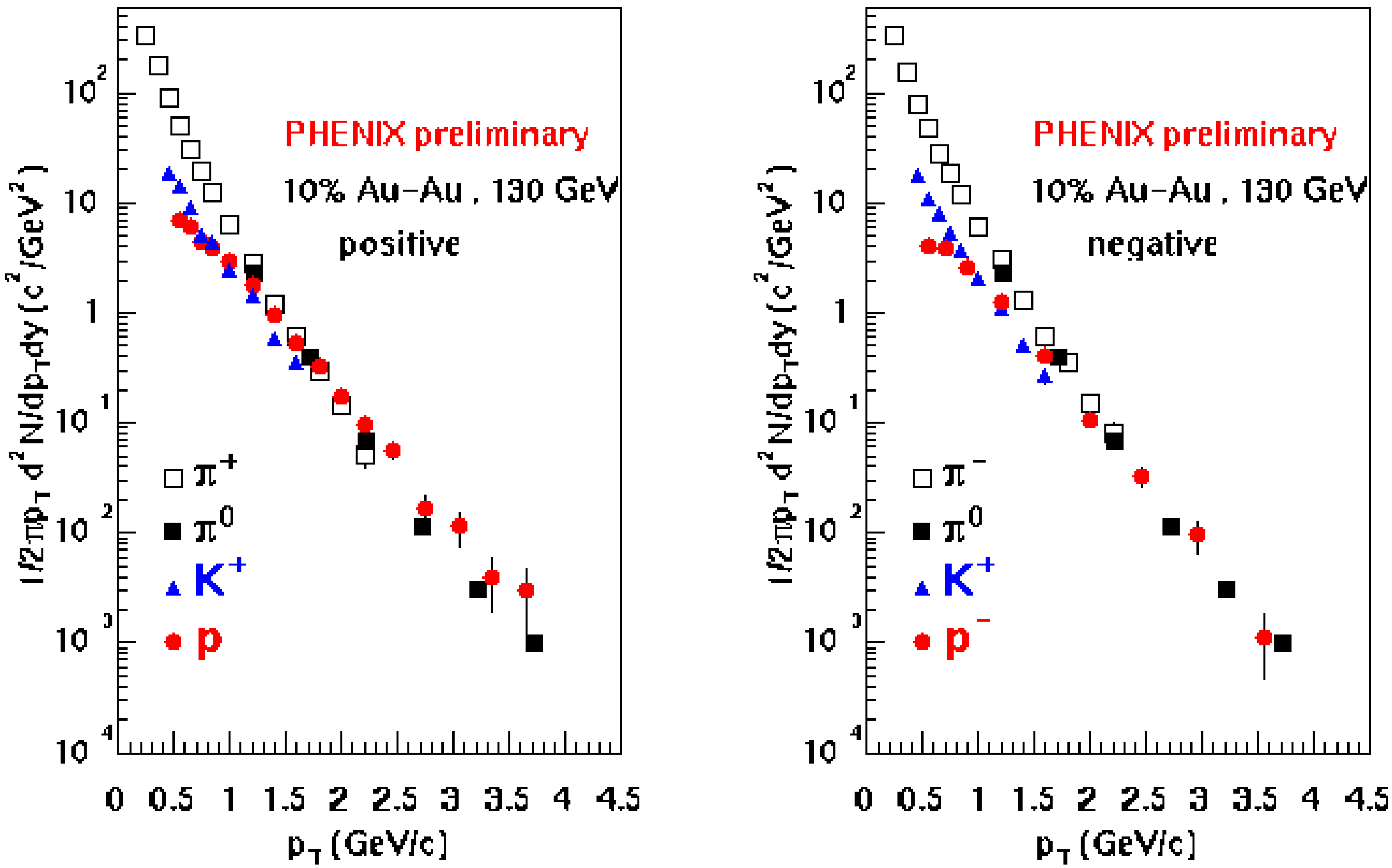
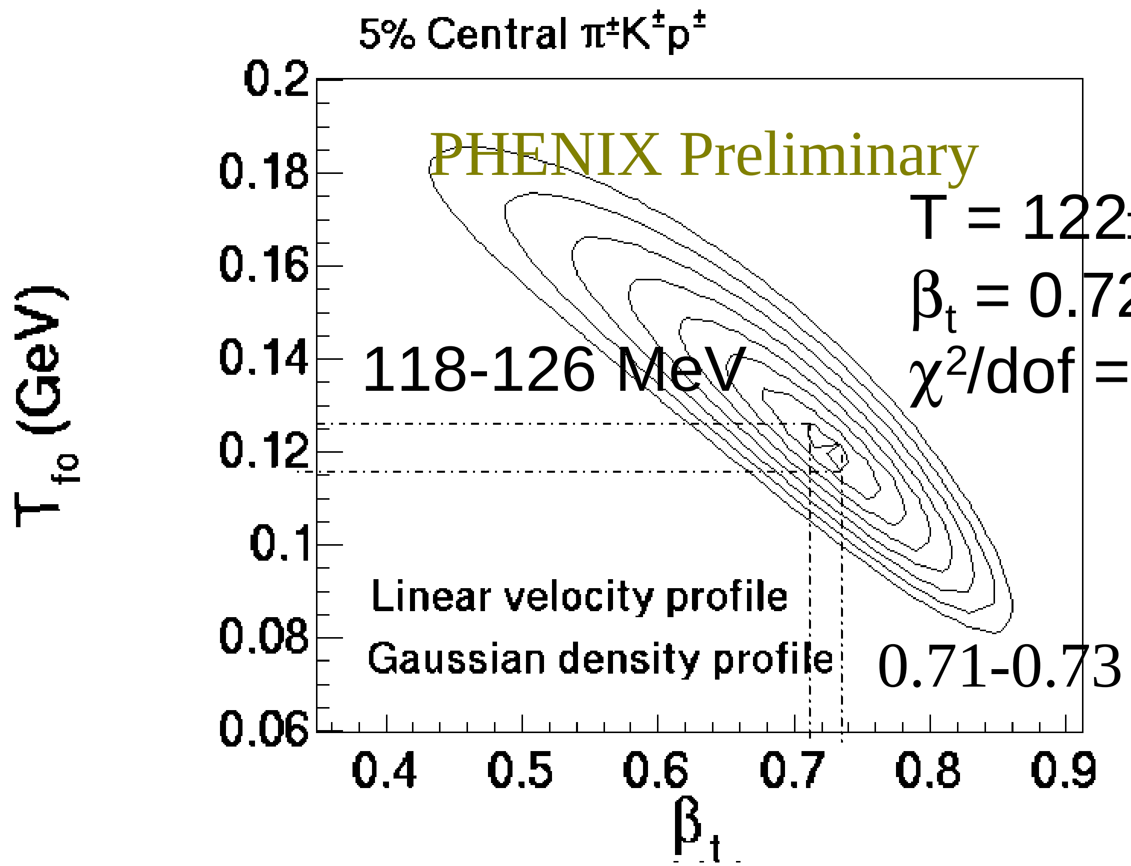
Transverse Momentum Spectra



- Excellent agreement between charged and neutral pions

5% Central Single Particle Spectra



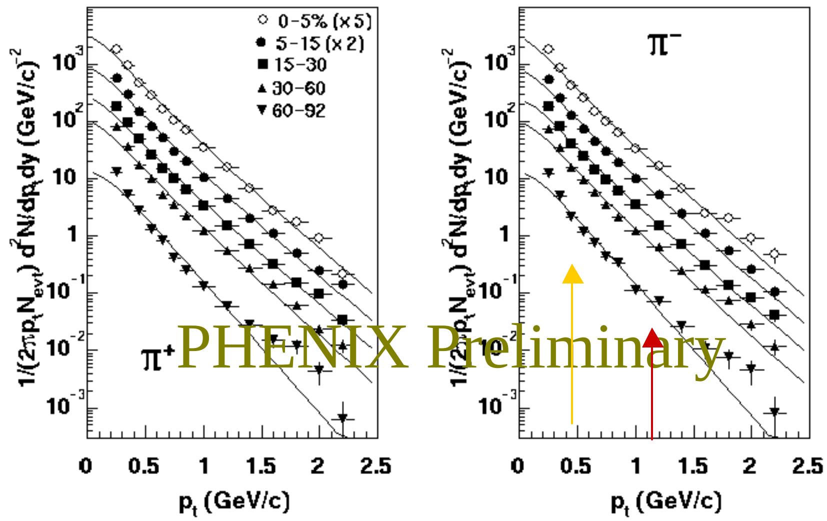
$T = 122 \pm 4$ MeV

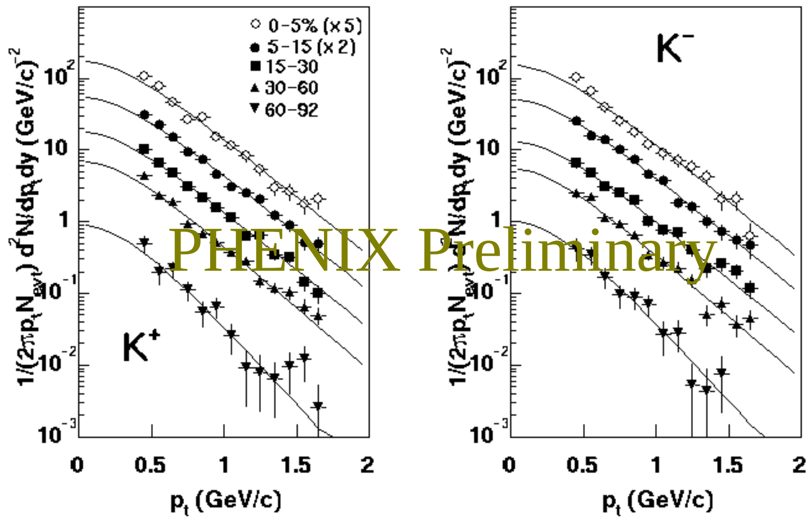
$\beta_t = 0.72 \pm 0.01$

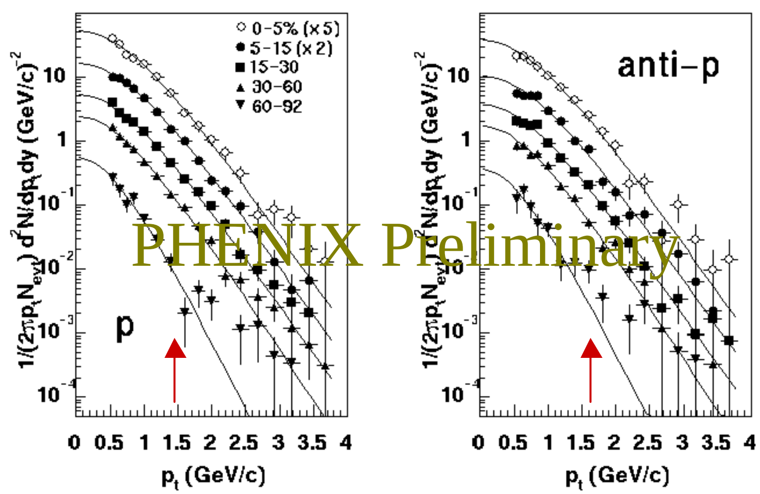
$\chi^2/\text{dof} = 30.0/40.0$

Fitting the Single Particle Spectra

Simultaneous fit $(m_t - m_0) <$ 1 GeV (see arrows)







Exclude π resonances by fitting $p_t > 0.5$ GeV/c

The resonance region decreases T by ~20 MeV. This is no surprise! Sollfrank and Heinz also observed this in their study of S+S collisions at CERN energies.

NA44 also had a lower p_t cut-off for pions in Pb+Pb collisions.

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Cooling then particle formation

The “temperature” we see is close to our expectations for the phase transition. It is hard to see a higher temperature from pions, kaon, protons, etc because they are produced after the system cools to the phase transition. We can only say clearly that the temperature was at least this high.

How do we measure density?

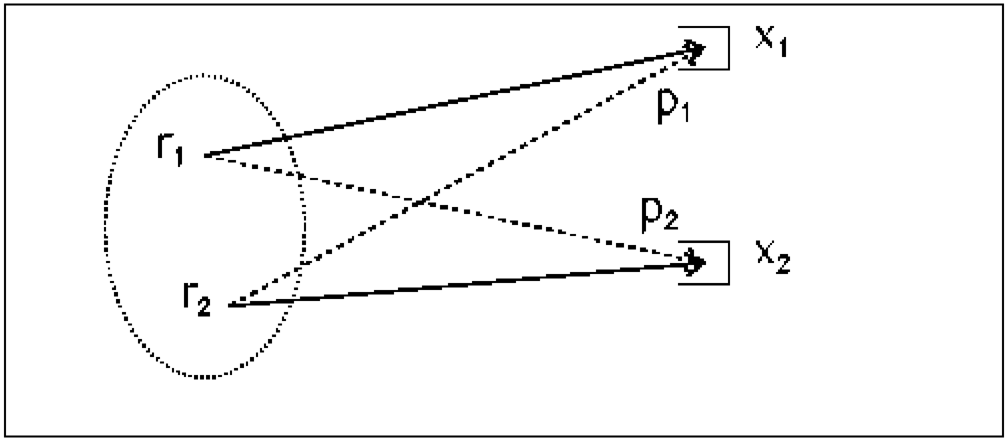
Initially, the transverse size is given by the collision geometry

can ~ “measure” the radii via two-particle interferometry

measure the total number of particles (~5000 max)

Gives ~ density

Two particle wavefunction



$$\phi_{12} = \phi_1(r_1, p_1)\phi_1(r_2, p_2) + \phi_1(r_1, p_2)\phi_1(r_2, p_1)$$

DEFINE: $\vec{q} \equiv \vec{p_2} - \vec{p_1}$, $\hbar \equiv 1$, $c \equiv 1$.

GIVEN: source distribution $\rho(r), (\int d^4r\rho(r) = 1)$

ASSUME: plane waves, no r,p correlation, ...

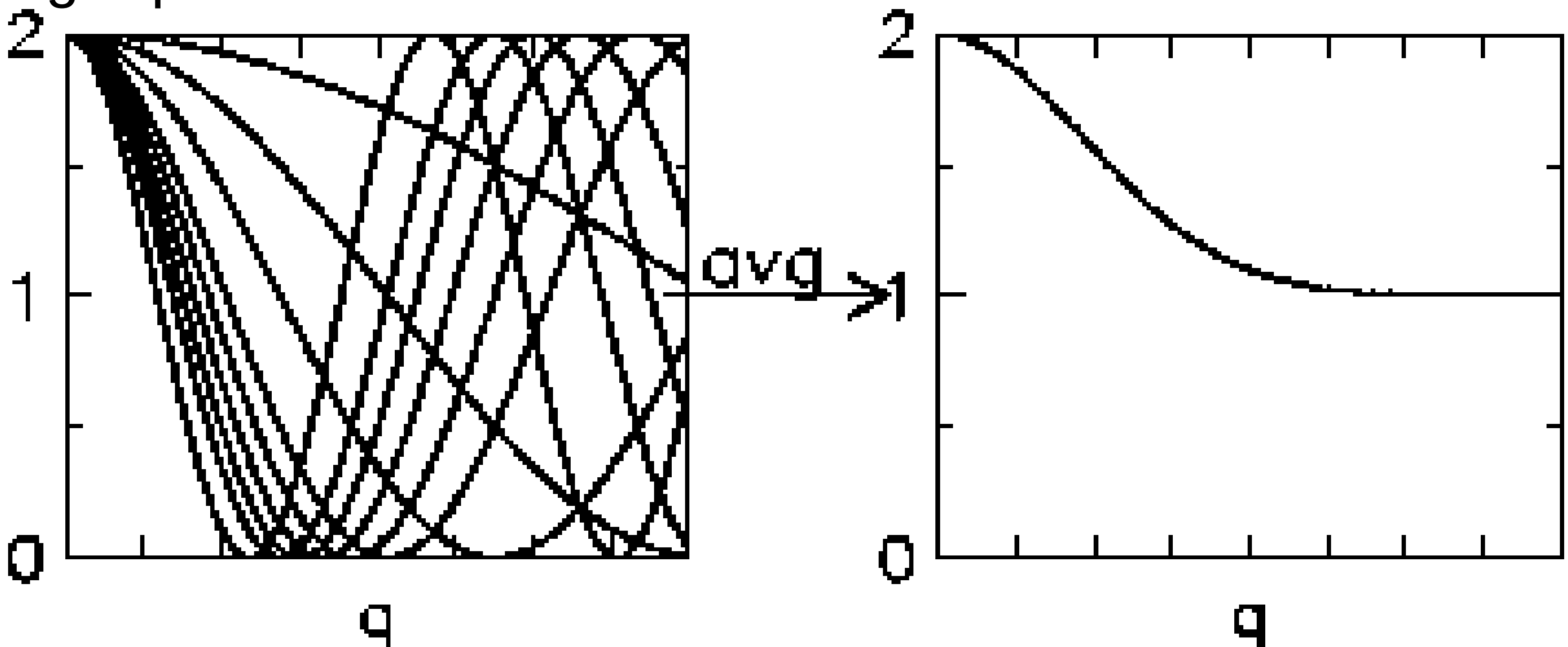
RESULT: $C_2 = 1 + |$ Fourier transform of $\rho(r)|^2$

EXAMPLE:

$$\rho(r) \propto \exp[-\frac{r^2}{2R^2}] \Rightarrow C_2 = 1 + \exp[-q^2R^2]$$

Average over positions in source

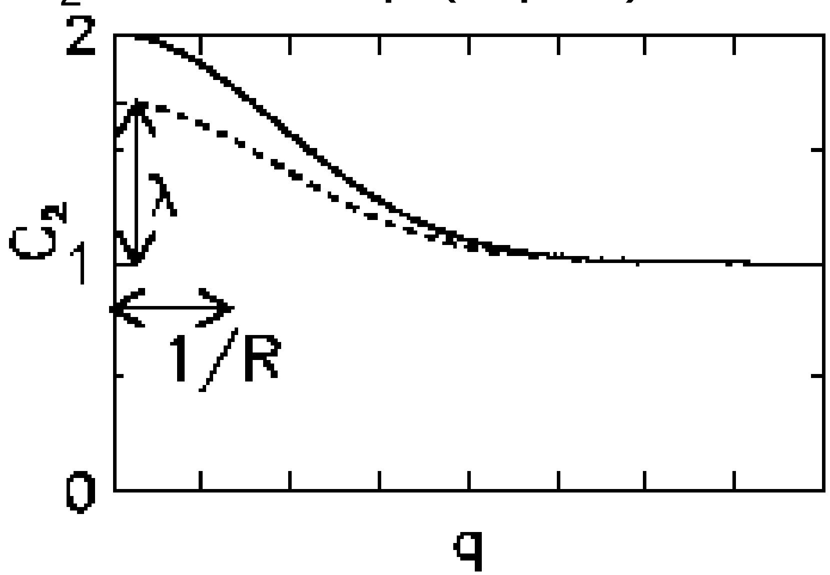
This plot tries to indicate how the average of many two particle wavefunctions (which each have a 1 + cos(q*dR) form) results in a 1 + exp($-q^2R^2$) form for the result. It is not quantitative. It is clear that C_2 = 2 at q = 0 and that C_2 = 1 at large q.



Correlation function

Typically fit data with:

$C_2 = 1 + \lambda \exp(-q^2R^2)$



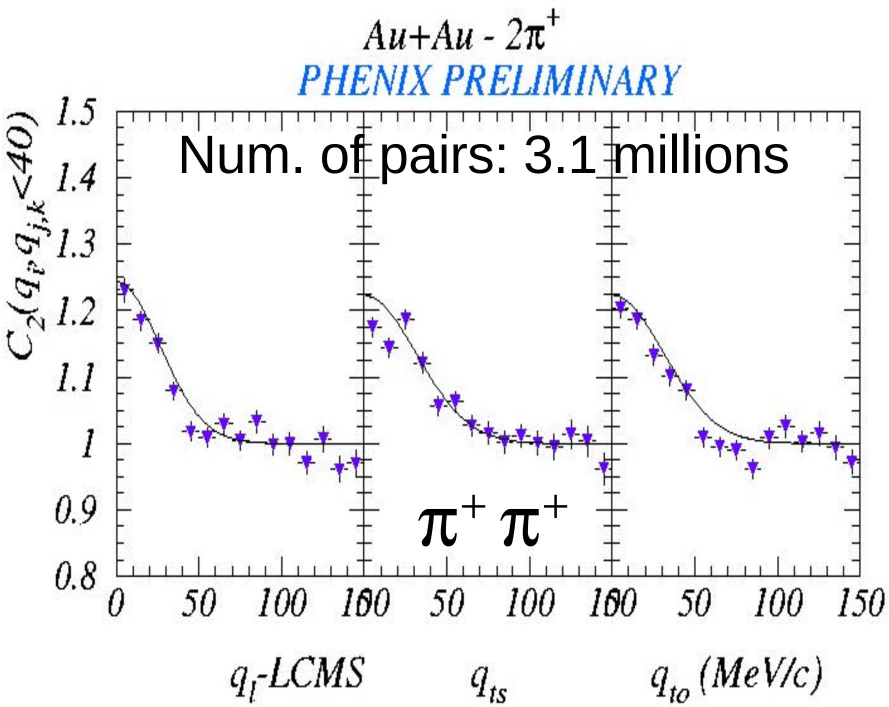
Experimental definition:

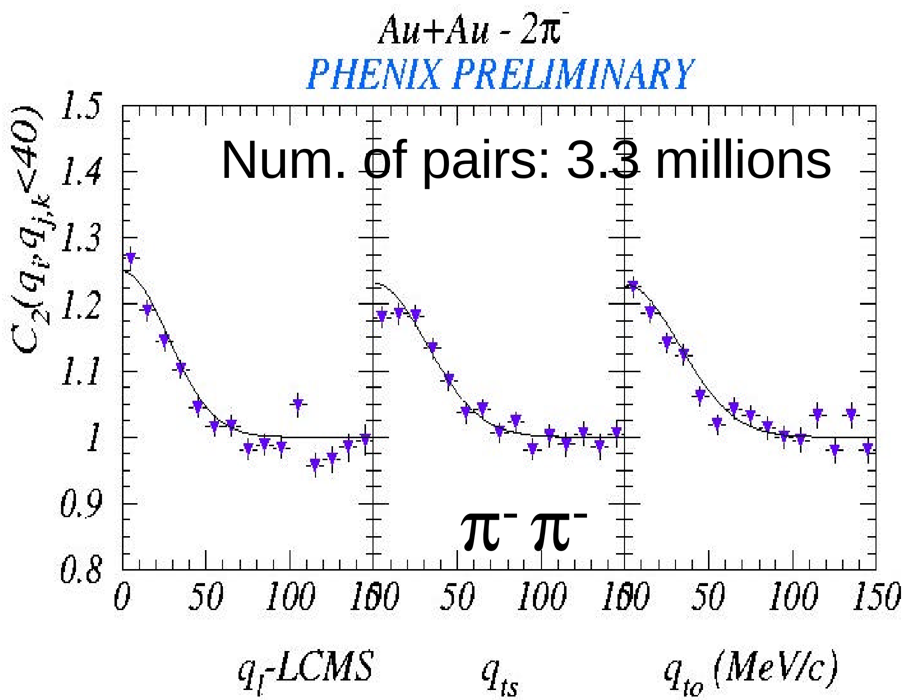
$C_2(q) \sim A(q)/B(q)$

$A(q)$ = actual distribution

$B(q)$ = background distribution -- mix real events

3-D correlation result



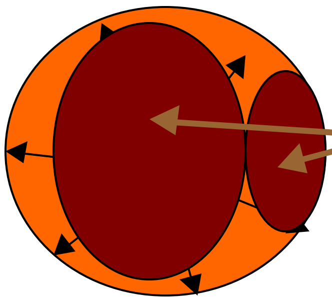


$\lambda = 0.395 \pm 0.026$
$R_{side} = 4.42 \pm 0.22$
$R_{out} = 4.45 \pm 0.22$ [fm]
$R_{long} = 5.28 \pm 0.32$

$\lambda = 0.399 \pm 0.026$
$R_{side} = 4.41 \pm 0.22$
$R_{out} = 4.30 \pm 0.24$ [fm]
$R_{long} = 5.13 \pm 0.26$

(Errors are statistical only)

K_T dependence of radius parameters



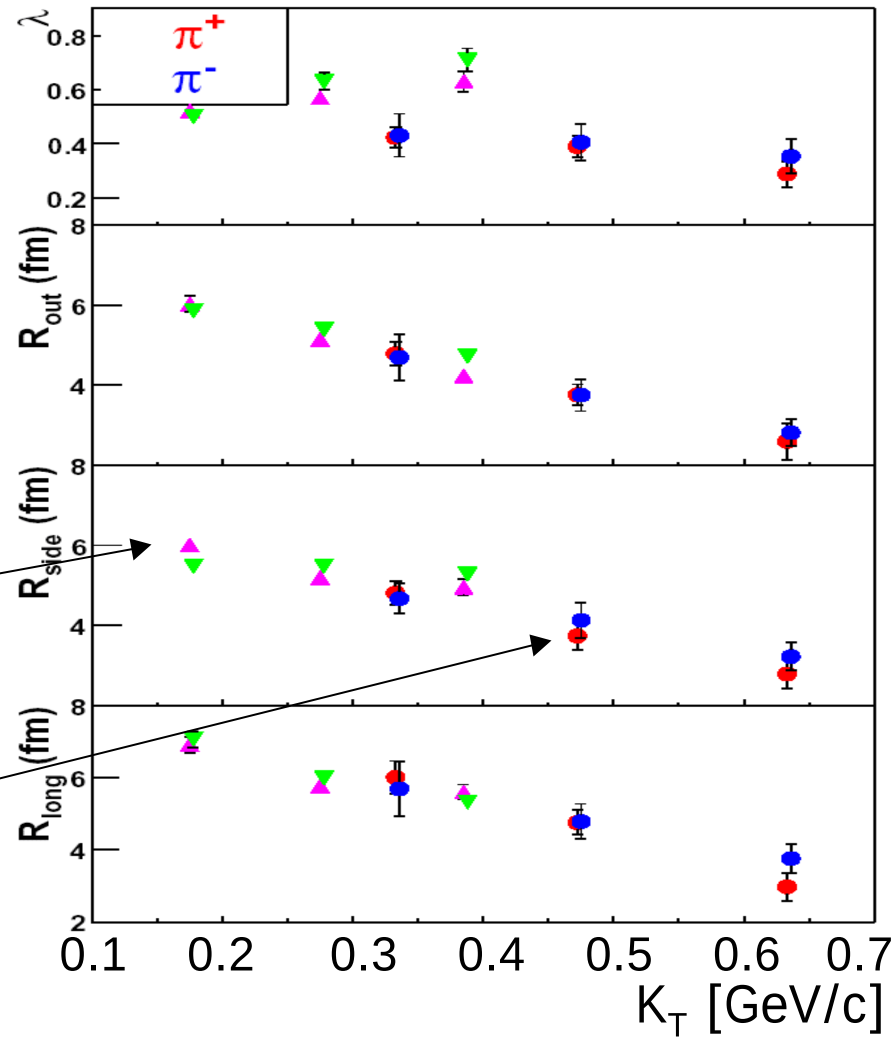
$$k_T = (p_{T1} + p_{T2})/2$$

We can see
"x-p correlation"
if there is collective expansion of the source

STAR's result ($\blacktriangle$ π^+ $\blacktriangledown$ π^-)

PRL 87 982301(2001)

PHENIX's result ($\bullet$ π^+ , $\bullet$ π^-)



Determining *Density*

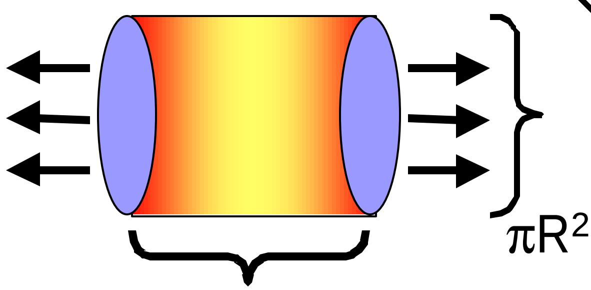
- What density is achieved?

"Bjorken" formula for density:

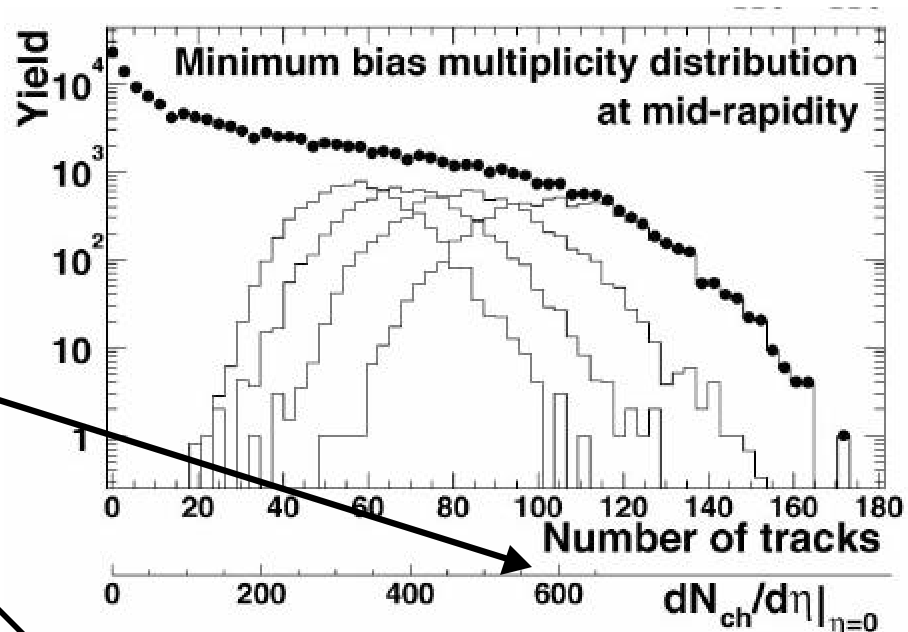
$$\rho_{Bj} = 1.5 \, \frac{1}{\pi R^2} \, \frac{1}{\tau_0} \, \frac{dN}{dy}$$

Add neutral particles

~6.5 fm



$$dz = t_0 dy$$

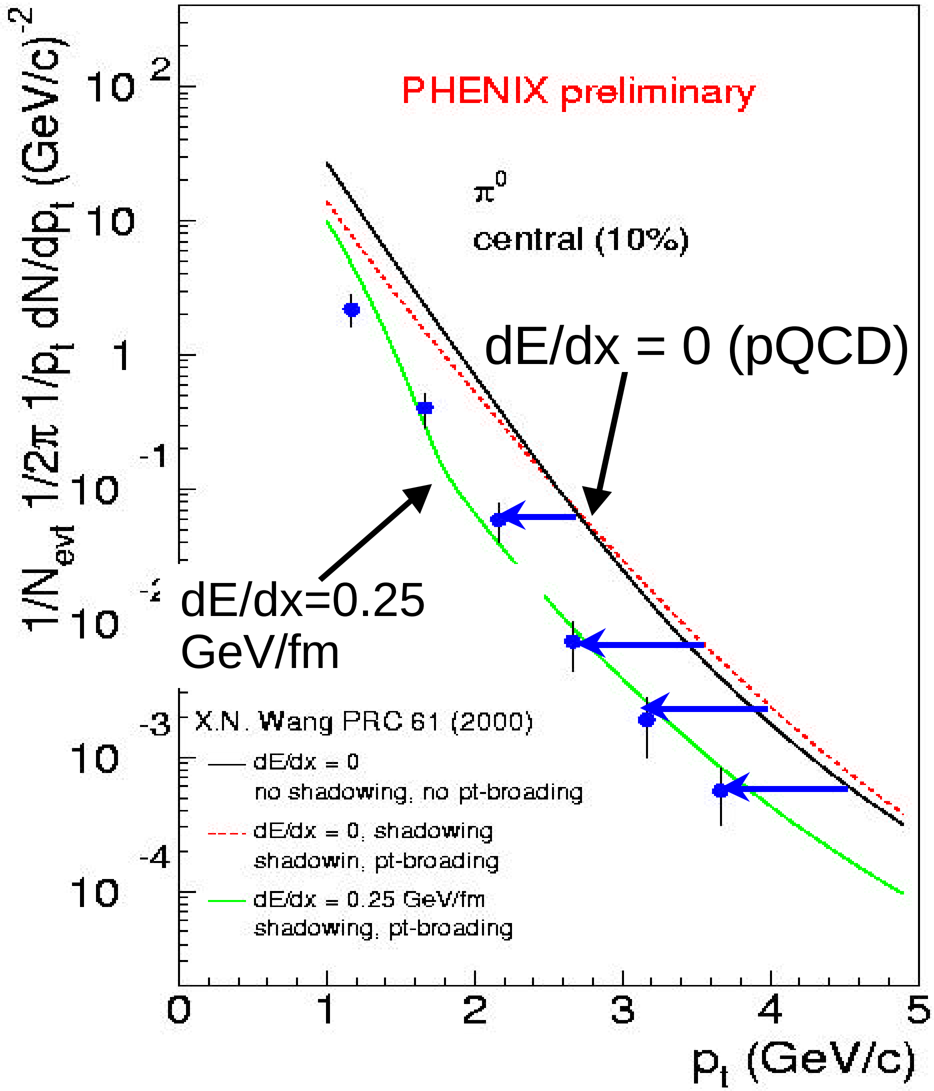


time to thermalize the system (t_0 ~ 1 fm/c)

$\rho_{Bjorken}$ ~ 6.8 particles/fm^3 = 30 - 40 times normal nuclear density

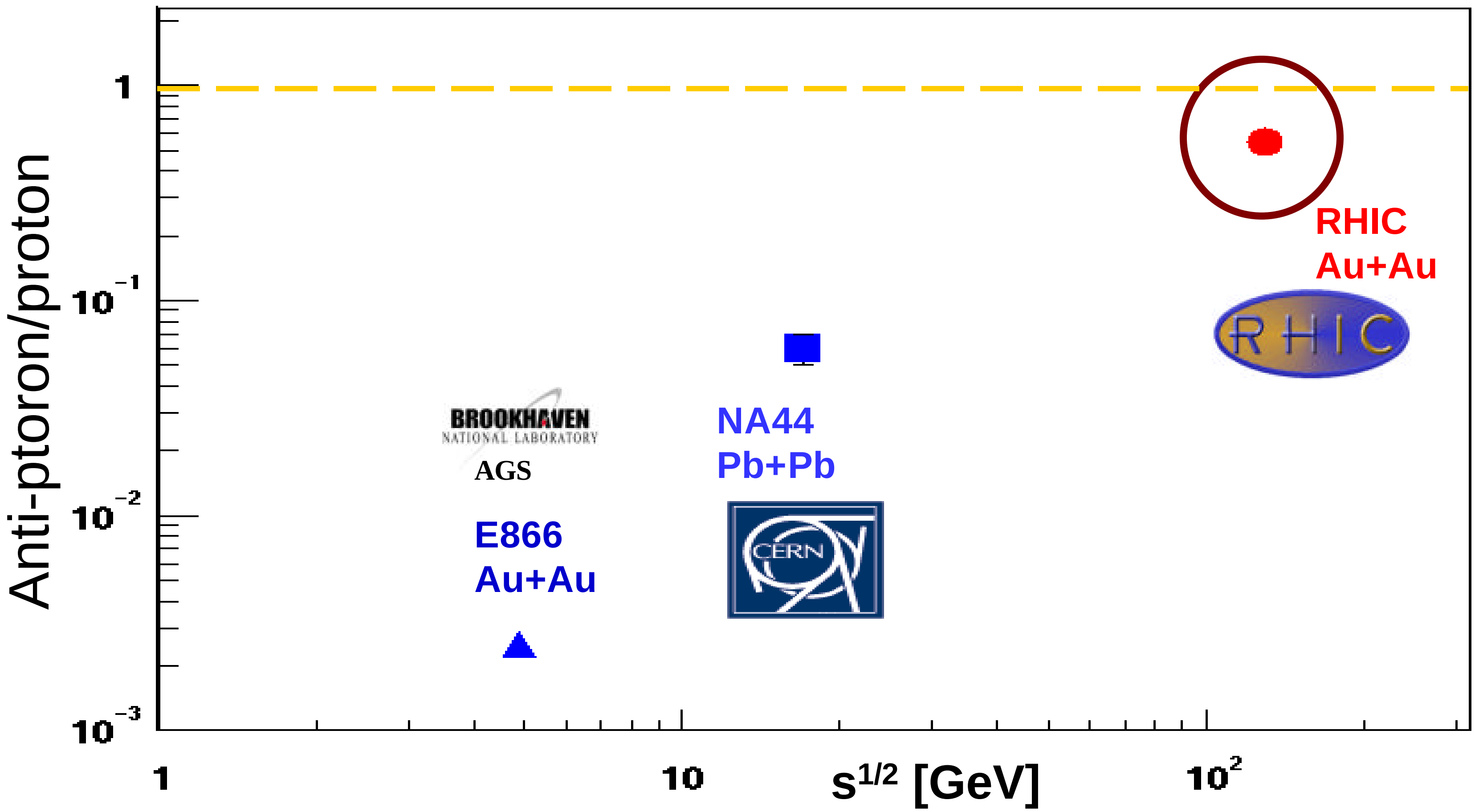
Central Events –
What's Going On?

- "Standard" predictions <u>overestimate</u> the cross-section for π^0 by at least ´5
- ***Predictions*** including (plasma-like!) energy loss ***consistent*** with π^0



Approaching the early universe?

In the Early Universe, the Anti-proton/proton = 0.999999999



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What is ahead?

The first high statistics Au+Au run ended ~Thanksgiving 2001.

Analysis is in progress, and the first round of results is expected this summer.

The plasma phase is hard to measure and only a careful study of all the signals will be conclusive.

Many of the most important signals require the higher statistics data from the new run.

For example, direct photon radiation from the plasma and “melting” of the J/Ø (c-cbar resonance)

Summary

- We understand the collision geometry (b)
- We understand the Temperature (T)
- We understand the density (ρ)
- Anti-particle/particle ratios approaching 1
- Elliptic flow results: initial spatial asymmetry translates to similar asymmetry in momentum
- The temperature and density measurements suggest that we are at or above the QGP phase transition. We need to look for signals.

Relevant Thermal Physics

Q. How to liberate quarks and gluons from
~1 fm confinement scale?

A. Create an energy density

$\varepsilon > \sim (\hbar c / 1\ \mathrm{fm})^4 \sim 0.2\ \mathrm{GeV / fm^3} \quad \sim \text{Normal nuclear density ??}$

Need better control of dimensional analysis:

$$\varepsilon = g \frac{\pi^2}{30} T^4$$

Energy density for "g" massless d.o.f

$$= \left\{ 2 \cdot 8_g + \frac{7}{8} \cdot 2_s \cdot 2_a \cdot 2_f \cdot 3_c \right\} \frac{\pi^2}{30} T^4$$

8 gluons, 2 spins;
2 quark flavors, anti-quarks, 2 spins, 3 colors

$$= 37 \cdot \frac{\pi^2}{30} T^4$$

37 (!)

$$\approx 12 \cdot T^4 \approx 12 \cdot \left(\frac{\hbar c}{1\ fm} \right)^4 \approx 2.4\ \mathrm{GeV / fm^3}$$

"Reasonable" estimate

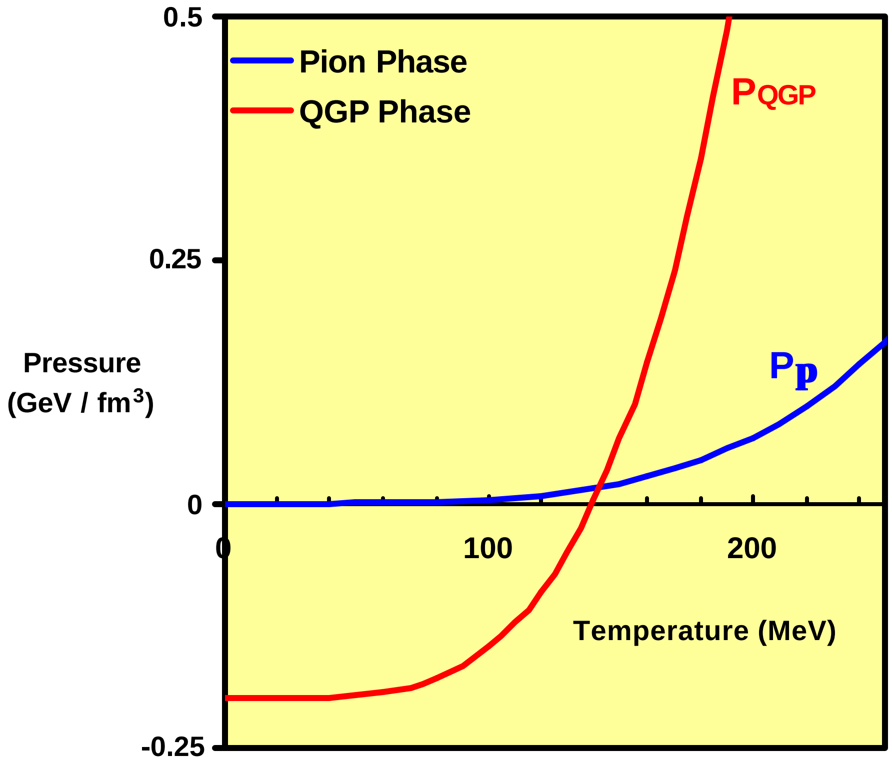
Rough Estimate

- *Compare*

$$P_\pi = 3\frac{\pi^2}{90}T^4$$ Pressure of “pure” pion gas at temperature T

$$P_{QGP} = g\frac{\pi^2}{90}T^4 - \mathrm{B},\ \ g = 37$$ Pressure in plasma phase with “Bag constant” B ~ 0.2 GeV / fm^3

- **Select system with higher pressure:**

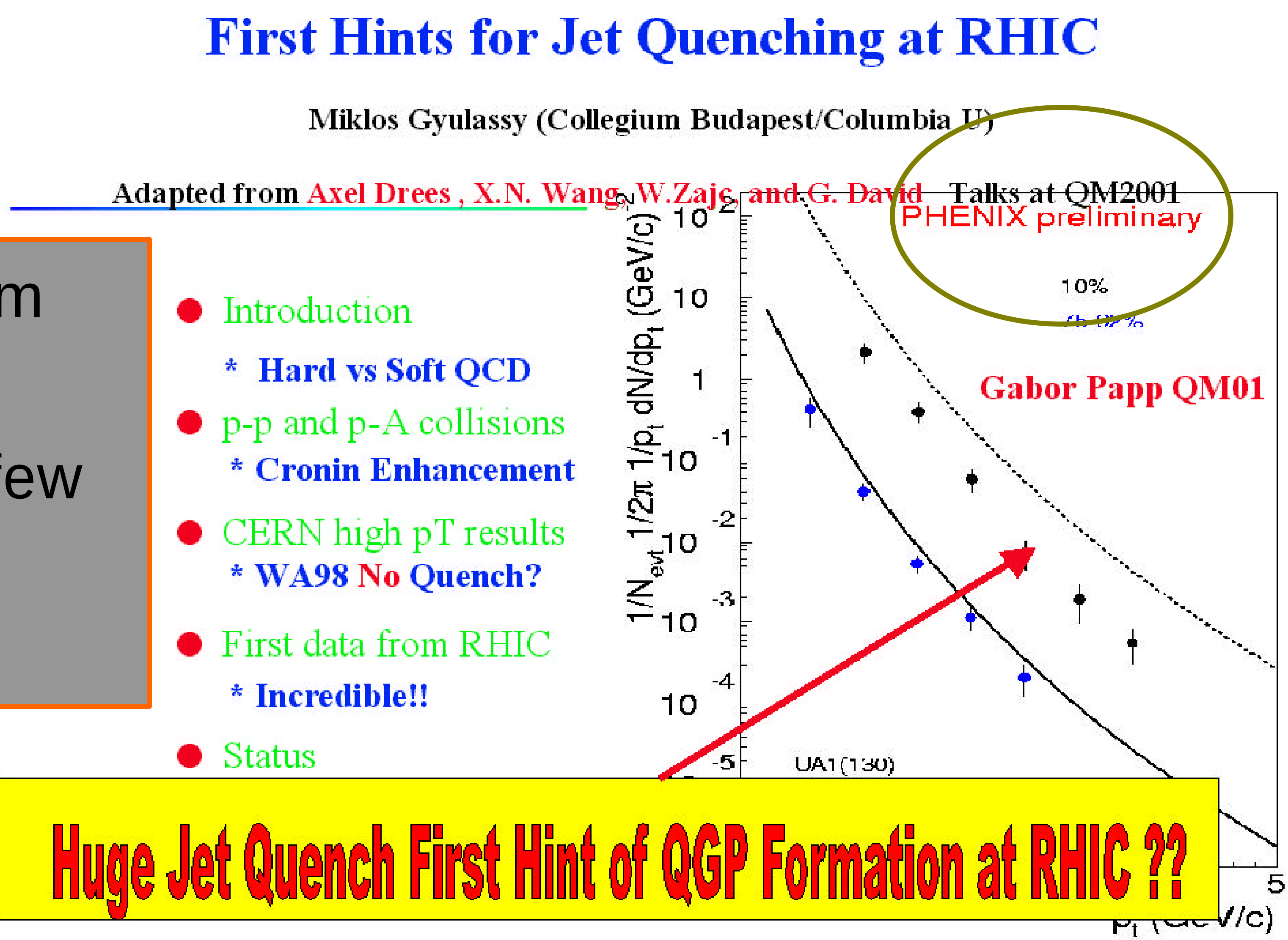


Phase transition at T ~ 140 MeV with latent heat ~0.8 GeV / fm^3

Compare to best estimates (Karsch, QM01) from lattice calculations:
T ~ 150-170 MeV
latent heat ~ 0.7±0.3 GeV / fm^3

Physics Implications (??)

Slide from [seminar](#) given a few



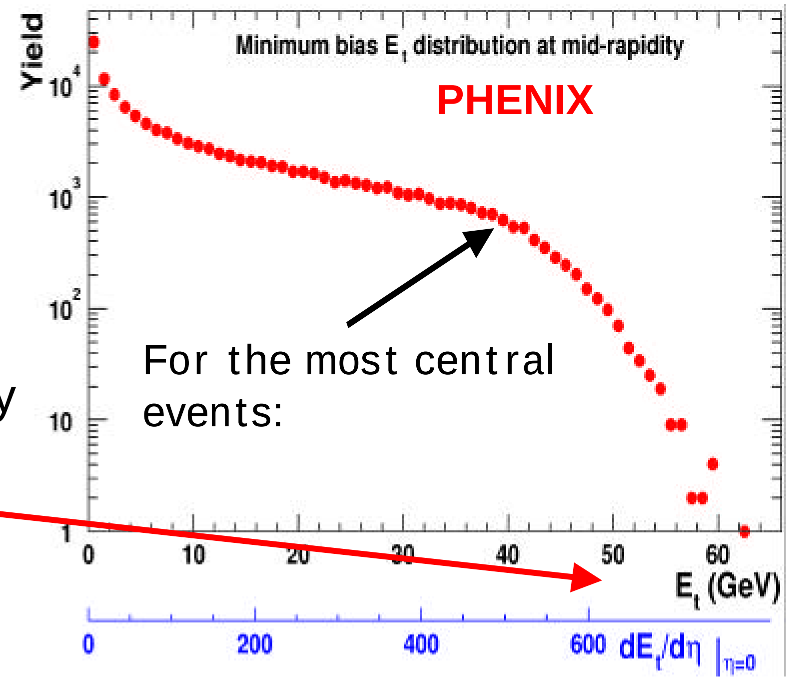
Huge Jet Quench First Hint of QGP Formation at RHIC ??

John Sulli

Determining Energy *Density*

- What is the energy density achieved?
- How does it compare to the expected phase transition value ?

EMCAL



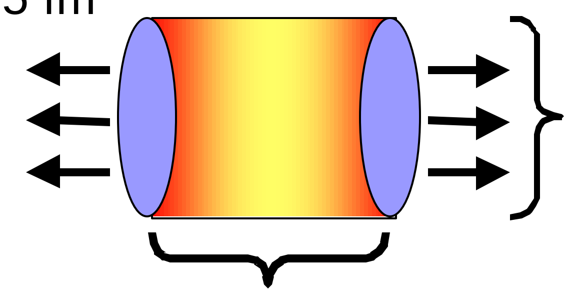
For the most central events:

Bjorken formula for thermalized energy density

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

~6.5 fm

time to thermalize the system ($\tau_0 \sim$ 1 fm/c)



πR^2

$$dz = \tau_0 dy$$

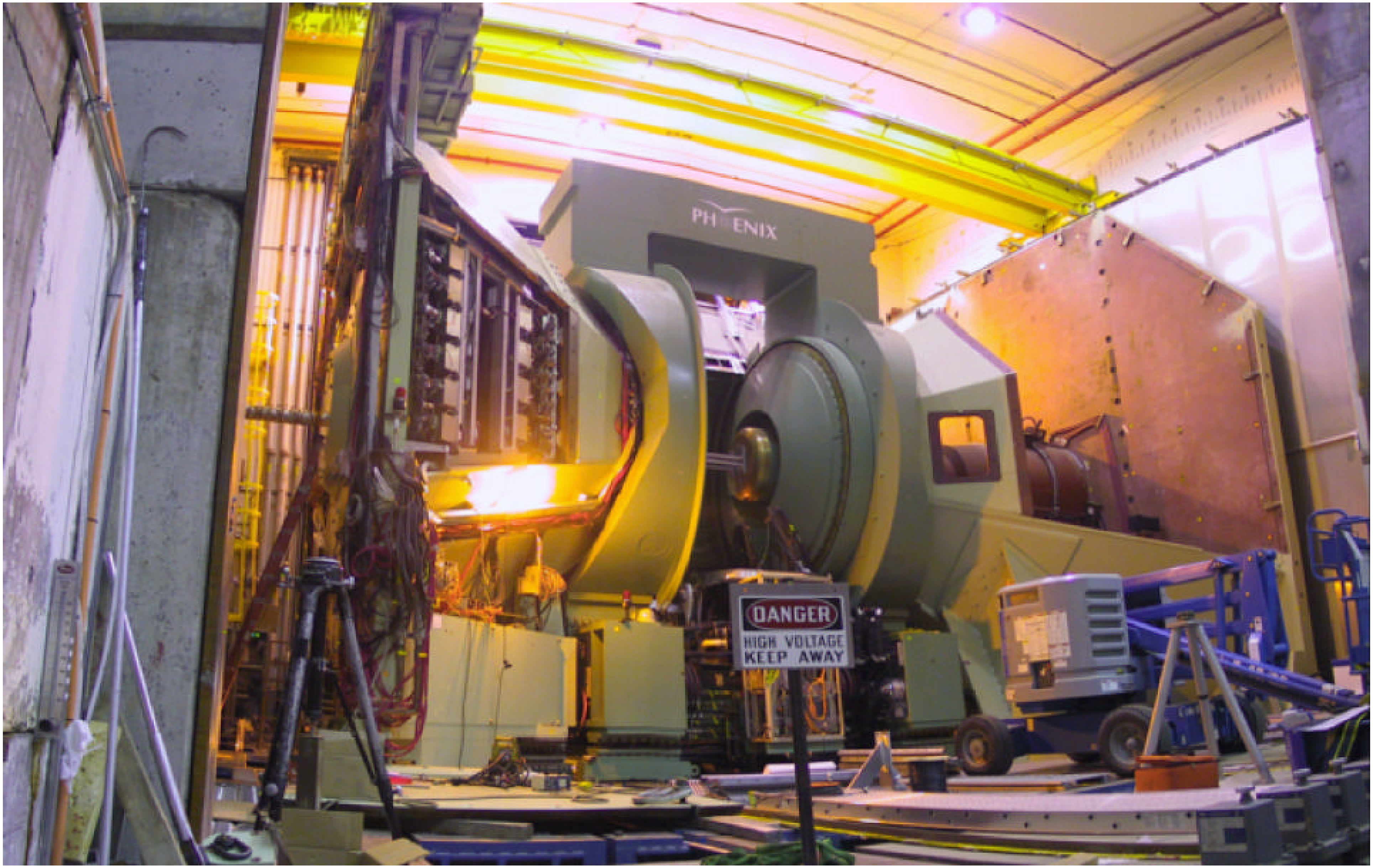
$\varepsilon_{Bjorken} \sim 4.6$ GeV/fm^3

~30 times normal nuclear density

~<u>1.5 to 2 times higher</u> than any previous experiments

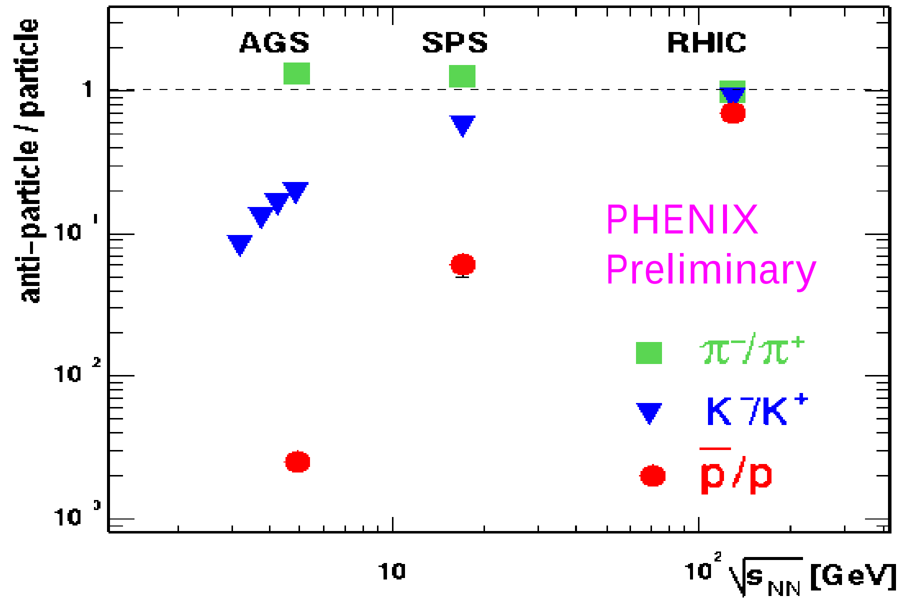
John Sullivan

Shape of Things Now



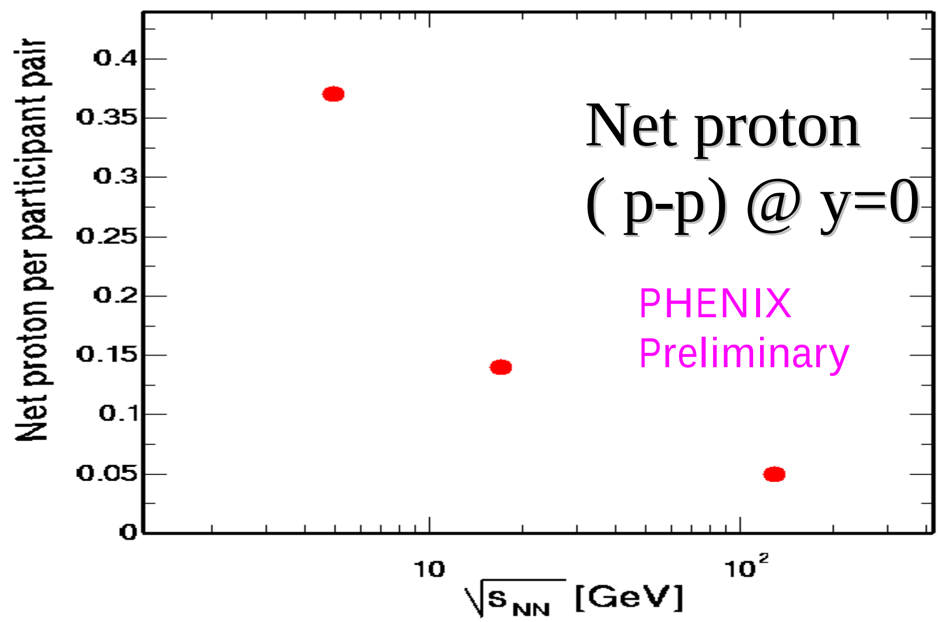
Collision energy dependence

- π-/π+, K-/K+ and pbar/p vs. collision energy.
  - anti-particle/particle ratios are dramatically increasing from SPS and AGS energies and approaching unity.

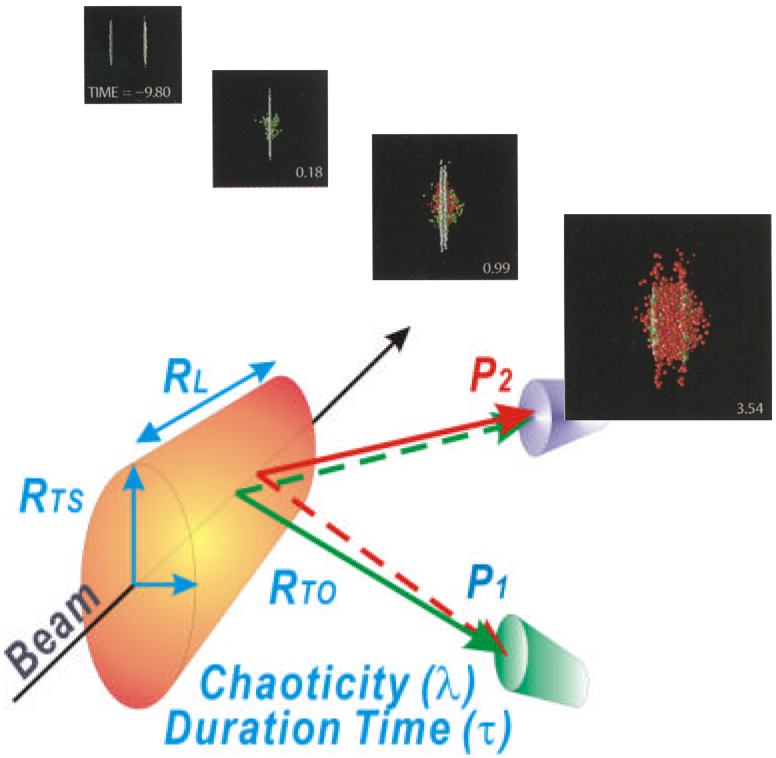


- (p-pbar)/(Npart pair) is dramatically decreasing from AGS and SPS energy

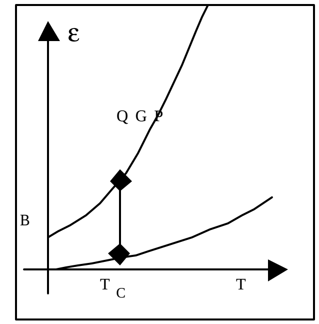
  RHIC : factor 7 smaller than AGS energy.

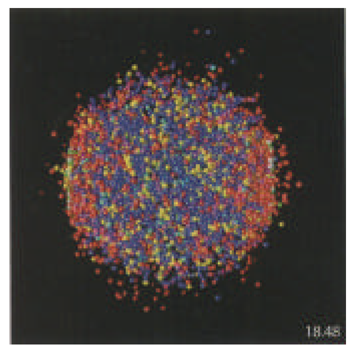


Particle correlations

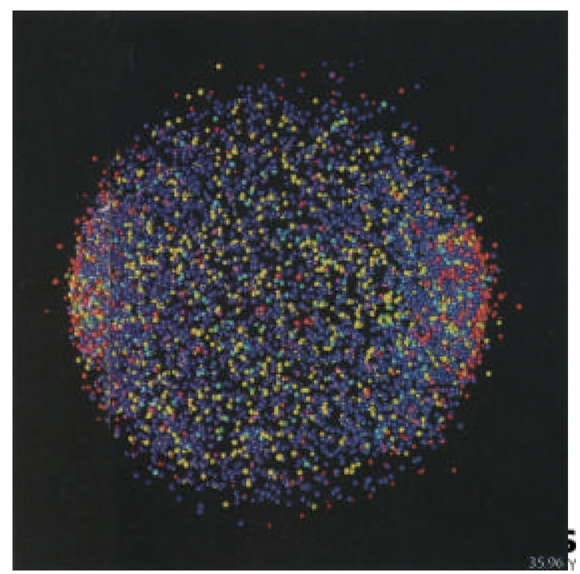


In the 1st order phase transition, matter of the mixed phases stops expansion due to the **softening of Equation of State**.





Consequently a **prolonged lifetime** of particle emission is expected.



$$\rho(\vec{r}, t) = \exp\left(-\frac{r_L^2}{2R_L^2} - \frac{r_{TS}^2}{2R_{TS}^2} - \frac{r_{TO}^2}{2R_{TO}^2} - \frac{t^2}{2\Delta\tau^2}\right)$$

In the LCMS frame

$$C_2 = 1 + \lambda \exp\left(-q_L^2R_L^2 - q_{TS}^2R_{TS}^2 - q_{TO}^2\left(R_{TO}^2 + \beta_{\pi\pi}^2\Delta\tau^2\right)\right)$$

$$\beta_{pair}^2\Delta\tau^2 \approx \left(R_{TO}^{exp}\right)^2 - \left(R_{TS}^{exp}\right)^2$$

$$R_{TO}^{exp}$$

John Sullivan

It might be valid for a static source, but our source is expanding..

Multiplicity Vertex Detector

- Two concentric barrels of 300μm Si strips
- Two endplates of Si pads
- Total coverage of -2.5 < η< +2.5
- 28,672 Si strips, 6048 Si pads
- Determines event vertex and measures particle multiplicity/event
- Electronics is bare die on ceramic Multi- Chip Module